DECEMBER 1986 VOL.8 NO.12

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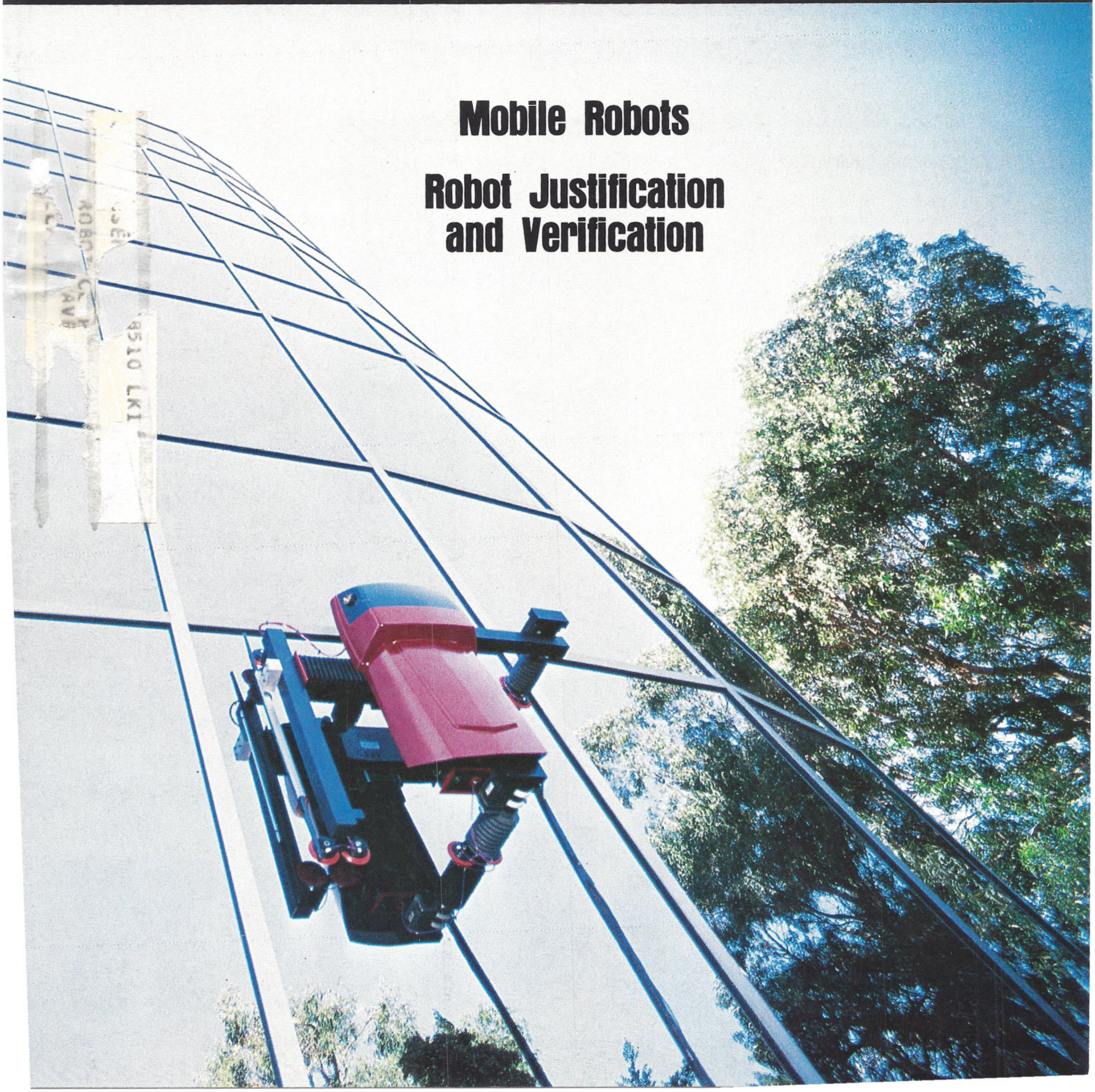
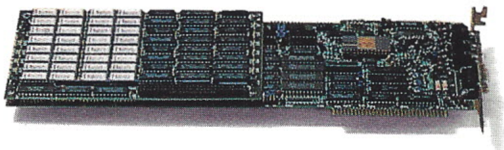
ROBOTICS ENGINEERING

THE JOURNAL OF INTELLIGENT MACHINES



Mobile Robots

Robot Justification and Verification



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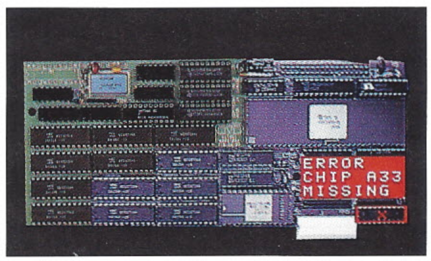

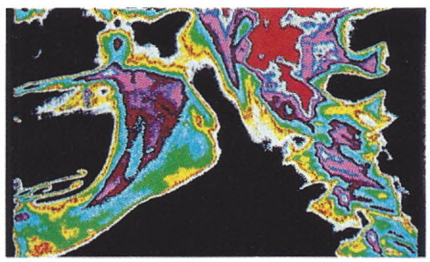

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ROBOTICS ENGINEERING

DECEMBER 1986 VOL. 8 NO. 12

EDITORIAL

FEATURES

DEPARTMENTS

About the cover: This month's cover photo, provided by International Robotic Technologies, depicts the Skywasher, an autonomous robot designed to wash down the glass facades of commercial buildings. The robot is described in the article beginning on page 27.

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Editorial

Diversify or Disappear

BY STEPHANIE vL HENKEL

We'll say it now and get it over with: Gloom and doom in the robotics market. Having said it, let's look at some causes and some possible cures.

The automotive industry has for all practical purposes subsidized the development of industrial robotics for the past 20 years. The two industries' fortunes were so inseparable that, while automotive's current slump may have come as a surprise, a parallel flattening on robot sales charts must be expected.

In addition to a slowdown in new orders, projections indicate two other trends in the robotics business, trends we do not like. The first is a turn away from diversity in the robots themselves. The fact that most were designed to plug into the existing, known requirements of only one industry, automotive, has led to "new" robots that look like minor variations on a theme rather than truly innovative designs. The other trend is toward a significant reduction in the number of robot manufacturers. If these trends continue, prospective robot buyers will have about as many options as purchasers of the Model T. Strange developments in a country noted for its heterogeneity and its devotion to technological breakthroughs.

Industries other than automotive have indirectly benefitted from whatever "robot revolution" there has been, and we believe it's time they got in on the act. The RIA has estimated that some 90 percent of the 60,000 to 70,000 industrial concerns that could be updated with flexible automation have not yet bought a single robot.

The best time to assess a situation and to think about ways of improving it is when things are fairly quiet. Now is the time to take a lesson from Japan, where robotics technology has been diversified from the get-go. Their approach is to examine a given industry or process and figure out how to develop the technology that will best automate it.

Three application areas come immediately to mind: food and beverage, pharmaceuticals, and service robots. Potential car buyers can decide to keep an old heap on the road for one more year, but they can't make a postponement decision about food or aspirin. With ever-increasing numbers of women, traditionally the domestic cooks, entering the workforce, the demand for pre-prepared food is soaring. There's another argument to be made for moving robots into these two industries—they won't turn terrorist and add rat poision to whatever they are preparing or packaging.

As for service robots, devices designed to help the ill, the handicapped, and the elderly, the issue is not simply a moral argument. Developing service robots makes good economic sense: There are a lot of disabled war veterans and other handicapped people who want jobs; enabling them to find work would be an asset to the country's economy. Also, America's population picture is changing; larger numbers of people with age-related infirmities will shortly constitute a sizeable market for the kinds of assistance service robots can provide.

All well and good, but where will the R&D money come from? Can robotics firms, even the largest ones, that are about to take a bath with the automotive industry afford to move into new areas? What about the smaller companies that survive the approaching shakeout? Can they spend five years laying out R&D dollars and waiting for a new product line to bring those dollars home again?

We don't know the specific answers. Perhaps we should ask the Japanese. We have read of the coalition in Japan among government, business, and education. Such an arrangement might work here and it might not. The truth is that there is money in America and there must be some way to channel it into economic improvement for the entire country. ■

Circle 32

Calendar

JANUARY

11–16. Optoelectronics and Laser Applications in Science and Engineering. Los Angeles Marriott and Airport Hilton Hotels, Los Angeles, CA. Contact: John Powers, International Society for Optical Engineering, PO Box 10, Bellingham, WA 98227-0010, telephone (206) 676-3290.

18–20. 1987 IEEE International Symposium on Intelligent Control. Hilton Hotel, Philadelphia, PA. Contact: IC-87 Organizing Committee, E.C.E. Department, Drexel University, 32 and Chestnut St., Philadelphia, PA 19104, telephone (215) 895-2220.

20–22. Workshop on Space Telerobotics. Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA. Contact: G. Rodriguez, M/S 198–330, Jet Propulsion Laboratory, 4800 Oak Grove Dr., Pasadena, CA 91109, telephone (818) 354-4057.

28–30. Computer Graphics New York '87. Jacob K. Javits Convention Center, New York, NY. Contact: Exhibition Marketing & Management Co., 8300 Greensboro Dr., Suite 690, McLean, VA 22102, telephone (703) 893-4545.

FEBRUARY

2–4. Instrumentation and Control Systems Short Courses. Orlando Airport Marriott, Orlando, FL. Contact: Instrument Society of America, PO Box 12277, Research Triangle Park, NC 27709, telephone (919) 832-5599.

3–4. Automated Clean Room Processes. Red Lion Inn, San Jose, CA. Contact: Diane Korona, Senior Program Administrator, Society of Manufacturing Engineers, One SME Dr., PO Box 930, Dearborn, MI 48121, telephone (313) 271-1500, ext. 390.

3–5. Manufacturing Productivity Conference & Exposition. Expo Centre, Orlando, FL. Contact: Public Relations Dept., Society of Manufacturing Engineers, One SME Dr., PO Box 930, Dearborn, MI 48121, telephone (313) 271-0777.

10–12. The Automated Manufacturing Show. The Montreal Convention Centre, Montreal, Quebec, Canada. Contact: Hugh F. Macgregor & Associates, 800 Denison St., Unit 7, Markham, Ontario, L3R 5M9, Canada, telephone (416) 479-3939.

10–12. Systems Design & Integration Conference. Santa Clara Convention Center, Santa Clara, CA. Contact: Electronic Conventions Management, 8110 Airport Blvd., Los Angeles, CA 90045, telephone (213) 772-2965.

17–18. Developing Practical AI Strategies for Manufacturing. Orlando, FL. Contact: Nancy Loerch, CASA/SME, Society of Manufacturing Engineers, One SME Dr., PO Box 930, Dearborn, MI 48121, telephone (313) 271-1500.

24–26. NEPCON West 87. Anaheim Convention Center, Anaheim, CA. Contact: Jerry Carter, Cahners Expo Group, PO Box 5060, Des Plaines, IL 60018, telephone (312) 299-9311.

MARCH

3–5. Laserobotics 2. Detroit, MI. Contact: Joanne Rogers, SME Special Programs Division, One SME Dr., PO Box 930, Dearborn, MI 48121, telephone (313) 271-1500, ext. 399.

In The Robotics Age™

Edited by Stephanie vL Henkel

MARKET RESEARCH

Shipments by U.S.-based robot suppliers rose 42 percent in dollar volume during the first half of 1986 as compared with the same period in 1985, according to new figures released by the **Robotic Industries Association**. Using a new method of reporting that reflects gross new orders and cancellations rather than net new orders, the organization assigned a $202.4 million dollar value to the 3236 robots shipped through last June. Shipments through June 1985 numbered 2764, with a value of $142.9 million. The second quarter of 1986 was particularly strong, with shipments coming in third at $119.4 million behind the third and fourth quarters of 1985. Gross new orders also took third place, but rose over 1985's second quarter: 1456 robots at $69.8 million to 1693 at $127.5 million. The picture is not so encouraging, though, in the light of a decline in gross new orders during the first half of 1986—down from last year's 3348 robots at $259.5 million to 3047 at $200.6 million. Backlog orders for the second quarter of 1986, while higher than the first quarter figure, were at their lowest point since the third quarter of 1984. Donald Vincent, RIA executive vice president, said that while declining orders and a lower backlog were causes for concern he remained optimistic about the long-term future of robotics. "Studies suggest that of the 60,000 to 70,000 industrial concerns in the United States, all of which can use robots, a very large percentage, at least 90 percent, have yet to install their first robot."

CORPORATE NEWS

► **GA Technologies Inc.** has received a $1.5 million contract to provide a robot operated radiography inspection system for the **U.S. Army**'s Yuma Proving Ground. GA will supply a robotic materials handling system to transfer ordnance items into and out of the radiography cell, where they will be inspected by an automated, real-time system. The Army will use the system to determine the positions of the arming and detonation mechanisms inside weapons.

► The **U.S. Army** Tank Automotive Command has awarded **KMS Fusion, Inc.** a $500,000 contract to develop an AI system that will perform path planning for unmanned military vehicles. Assisting in the project will be Lear Siegler's Instrumentation Division and the Environmental Research Institute of Michigan. Lear Siegler will provide navigational systems and computer programs for route selection, and ERIM will combine large geographical databases into a single, high-resolution digital database.

Robot Testing and Evaluation

Albert J. Sturm and **Ivor Matz**
CIMCORP Inc.
Robotic Systems
899 West Highway 96
St. Paul, MN 55126

One indication that our industry is maturing is that users are asking for increasingly sophisticated information on robot performance. The day is long gone when most robot users were R&D engineers content simply to "turn it on and see what happens." Today, client industries are demanding—and getting—comprehensive test and evaluation data on robot systems before they ever sit down and talk with a salesman. And it's just as likely that the purchase contract requires a certification test on the actual robot the customer buys.

The fallout of this increasing sophistication on the customer's part is confusion throughout the industry. There are at present no industry-wide standards governing how robots should be tested, what methods should be used, what test criteria are acceptable, and how the results should be interpreted. To add to the confusion, there are a great variety of robots on the market with diverse architectures that must be taken into account when testing. Also, while many robots are directed toward specific applications such as assembly, material handling, spray painting, or welding, others are more versatile. Thus, performance characteristics that make a robot a good candidate for one application make it a poor candidate for a different one.

The lack of standards has led to claims and counterclaims by robot manufacturers who base their specifications on individualized test methods, and has tempted some to offer optimistic operating specs and idealized performance data. Too often, the result is that the customer gets a nasty surprise when a robot doesn't perform as well as expected. We need to establish comprehensive test parameters and a methodology for various types of robots so users can compare apples to apples when making their selections. That's not likely to happen soon though, so in the meantime users will have to learn to interpret the data they receive from robot vendors, which entails an education in the fundamentals of robot testing and evaluation.

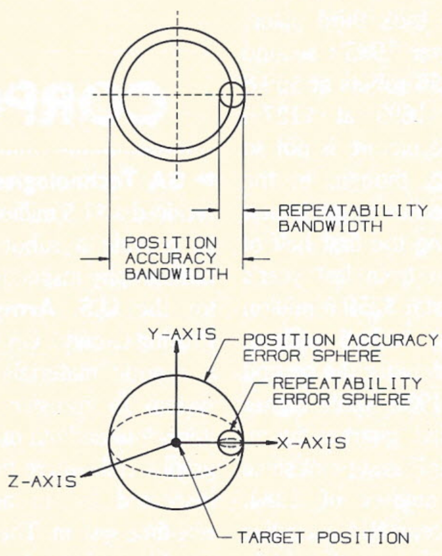


Figure 1. The tolerances of a target point specified for accuracy and repeatability can be thought of as the radii of imaginary spheres surrounding the target, an actual point bull's eye in 3-D space.

As the leading manufacturer of gantry robots worldwide, at CIMCORP Inc. we've learned that market demand drives test technology. As our robots become increasingly powerful and accurate, our most sophisticated customers have presented us with formerly impossible applications that push the new robot designs to their operational limits. Consequently, in order to establish the suitability of our gantry robots for a particular application, we've been forced to develop a comprehensive testing and evaluation methodology. While our methods are tailored for gantry robots, the methodology is based on conservative principles that relate to other types of robots as well.

DEFINING TERMS

The first hurdle to overcome in pro-

viding meaningful test data to customers is to make sure you're both speaking the same language. To that end, it helps to define terms—especially when discussing robot performance. Currently, the robot performance data most in demand includes **position accuracy, repeatability, resolution**, and **hunting**. Of all robot performance characteristics, position accuracy and repeatability are the most confusing and the most subject to widely varying interpretations and claims. Robot performance is usually specified entirely as repeatability, even though repeatability often is only a small part of position accuracy. The terms are not interchangeable; they are separate concepts, and their relative importance depends on the intended robot application.

Position accuracy is the robot's degree of precision in its initial attempt to reach a target point, as in process applications. The point obtained must be within a specified tolerance of the target point, a point usually programmed off line. This specified tolerance can be thought of as the radius of an imaginary sphere surrounding the target point bull's eye in three-dimensional space (Figure 1). The sphere represents the total position accuracy error bandwidth of the robot. Note that position accuracy includes repeatability.

Repeatability is the robot's degree of precision in returning to a previously acquired point, as in pick and place applications. The repeated point must be within a specified tolerance of the previously obtained point. This specified tolerance can be thought of as the radius of a second imaginary sphere surrounding the previously obtained point bull's eye in three-dimensional space. As shown in Figure 1, the repeatability sphere is smaller and contained somewhere within the position accuracy sphere. This second sphere represents the robot's total repeatability error bandwidth.

Resolution is the smallest unit of motion the robot can achieve. It is limited not only to the smallest increment of the position-feedback system, but is also affected by transducer placement (at rear of motor or at output of gearing), servo compensation, the servo components (i.e., DACs), mechanical backlash, and so forth.

Hunting is the oscillation of a robot at a stationary position due to quantization error (the dead zone between transducer counts), output shaft windup, coefficients of friction, and mechanical backlash.

TEST METHODOLOGIES

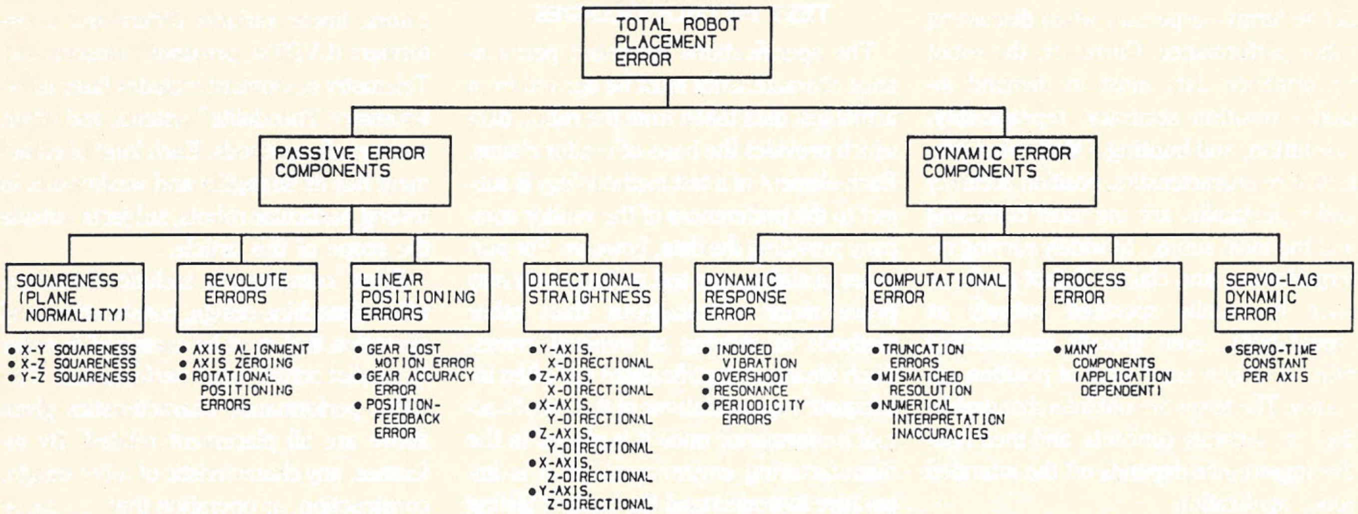
The specifications for robot performance characteristics must be derived from actual test data taken from the robot, data which provides the basis of vendor claims. Each element of a test methodology is subject to the preferences of the vendor company providing the data, however. For purposes of claims, one test methodology may prove more advantageous than other methods in arriving at minimal errors. Such idealized specifications are often inadequate representations of the robot's actual performance once it is placed in the manufacturing environment, so it is imperative to understand the basis of testing to obtain a correct understanding of robot performance.

There are four major elements of a robot test methodology: **methods of measurement, error components, test criteria**, and **test standards/data interpretation**.

Methods of measurement include the kind of testing done (point-to-point vs. path control) and the type of equipment used in the test. Both methods of testing can be performed using displacement transducers or telemetry equipment. Displacement transducers include dial indicators, linear variable differential transformers (LVDTs), proximity sensors, etc. Telemetry equipment includes laser interferometry, Theodolite® systems, and other, more exotic methods. Each kind of equipment has its strengths and weaknesses in testing particular robots, subjects outside the scope of this article.

Error components include characteristics of machine design, construction, and operation that must be examined in order to predict actual robot performance. The robot performance characteristics given above are all placement related. By inference, any characteristic of robot design, construction, or operation that can cause a deviation in "perfect" placement of the robot tool tip must be included in the test methodology as a source of placement error. For purposes of testing, these error components can be broadly grouped into two categories: passive errors and dynamic errors (Diagram 1). Passive errors reveal how closely the mechanical system adheres to a mathematical ideal in design and construction. Minute mechanical and geomet-

Diagram 1
Robot Passive and Dynamic Position Errors



rical imperfections—normal to any machine—result in measurable deviations from the mathematical ideal that contribute to robot placement error. Dynamic errors occur as a result of kinematic influences as well as small servo control errors—normal to any servo controlled machine.

Test criteria include many different factors such as unidirectional vs. bidirectional measurements, the positions at which the measurements were taken, the number of measurements taken at each position tested, the dwell (settling) time at each position tested, the robot orientation at each position tested, warm-up time, and payload. Since these factors are too complex to be rendered on a simple spec sheet, ask the vendor for a copy of the checkout procedure if you have questions.

Test standards/data interpretation include two recognized standards that describe test methodologies for measuring the linear position accuracy of machine tools: The National Machine Tool Builders Association's *Definitions and Evaluation of Accuracy and Repeatability for Numerically Controlled Machine Tools*, Second Edition, August 1982, and *European Machine Position Accuracy Standard VDI 3441*. These standards cover only *linear* position measurements; their application to process robotics will be examined throughout the remainder of this article. It is important to note, however, that they are inadequate for testing robots, which are typically much lighter than machine tools and operate within much larger work envelopes. Also, many robot designs—such as gantry robots—are not well governed by the standards, so it becomes necessary to find ways to accommodate the intent of the standard while still obtaining valid results. For example, a gantry robot usually has a vertical mast that travels along the z axis. This massive, cantilevered appendage with its small support aspect ratio introduces significant Abbe errors that degrade overall robot performance. Figure 2 illustrates the way Abbe errors can aggregate to contribute to linear position error. Position measurements must therefore be taken at the axis positions that will generate the worst-case Abbe errors to accommodate the intent of the standard, while capturing data that will adequately represent robot performance. In gantry robots, worst-case Abbe errors are usually generated when the mast is fully extended at the center of the work envelope.

Figure 3 depicts some of the definitions of the aforementioned standards. Seven discrete bidirectional measurements (14 passes) for a single point are represented as bar graphs for both forward and reverse directions. The values of the measurement samples (representing robot placement error) cluster on either side of the zero error line (representing perfect placement), separated by the amount of backlash or lost motion in the mechanical system. Corresponding Gaussian distributions for each direction are over-plotted to represent the

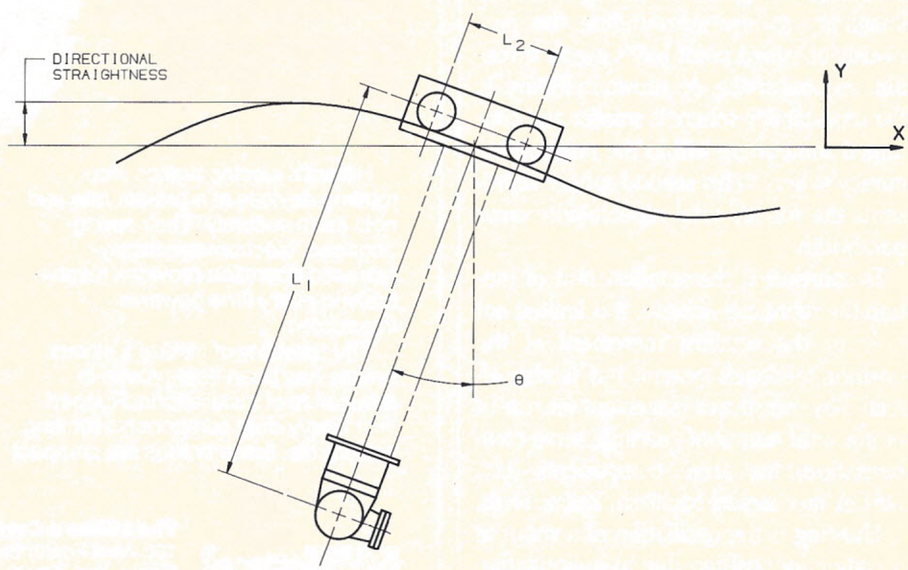


Figure 2. Robot architecture makes existing machine tool test standards inadequate. For example, gantry robots usually have a vertical mast that introduces significant Abbe errors not covered by many standards.

MARTIN MARIETTA BALTIMORE AEROSPACE

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MARTIN MARIETTA

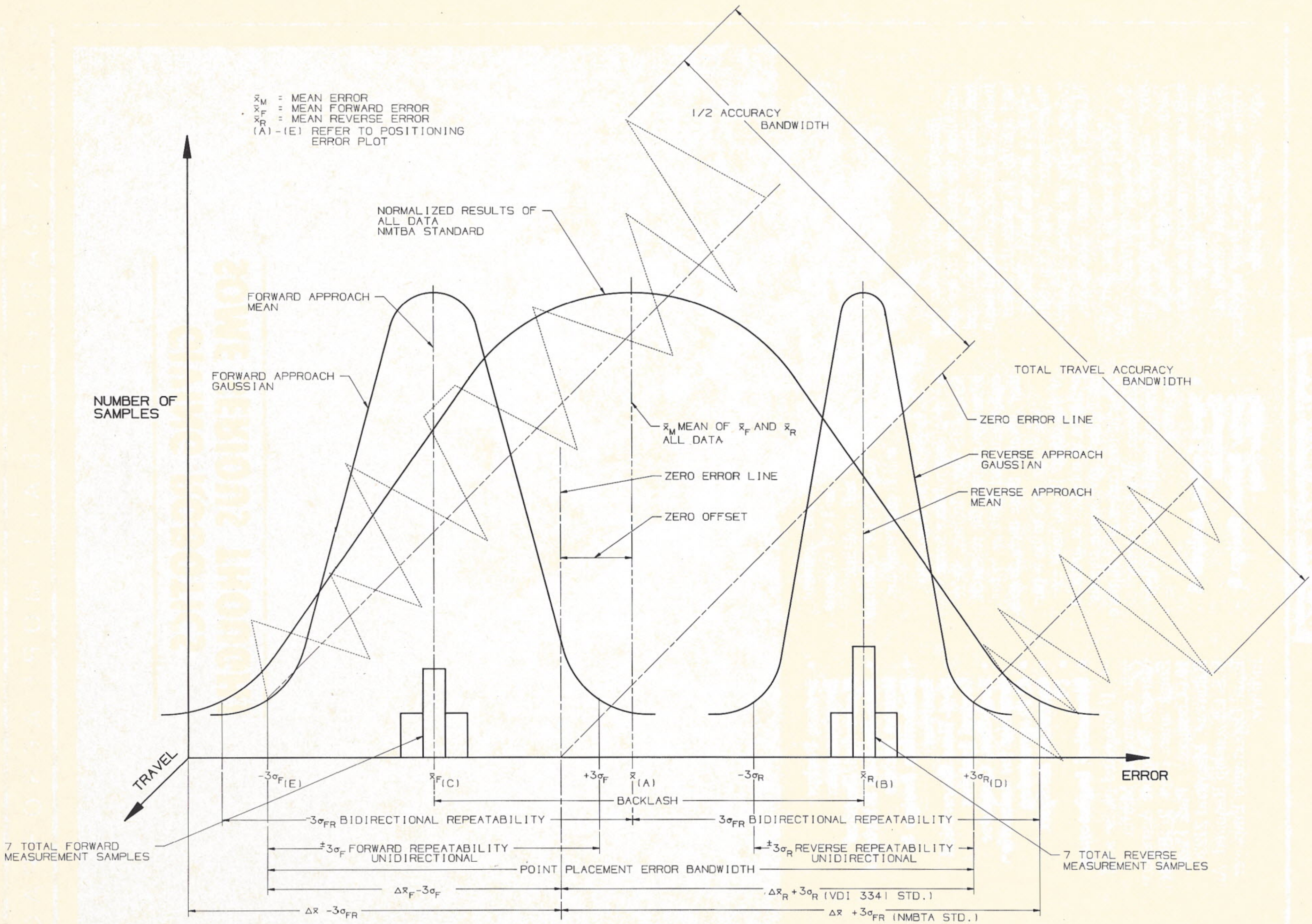

Figure 3. The values of the test measurement samples (representing robot placement error) cluster on either side of the zero error line (representing perfect placement), separated by the amount of backlash or lost motion in the mechanical system.

dispersion of an infinite number of test samples, in accordance with standard statistical practice. About 99.74 percent of probable test measurement values are covered by employing 3-sigma values generated from the mean value of placement error for both sets of measurement samples (for 2-sigma dispersion, this figure would be 95.44 percent). Thus, the *total* placement error for the point (point placement error bandwidth) is any difference between the actual robot position and perfect placement (zero error line).

Position accuracy for the point is altogether a different case from that of robot placement error. Position accuracy for any specific point is equal to the sum of the signed value of the mean error ($\overline{X}_M$, $\overline{X}_F$, $\overline{X}_R$) plus the value of dispersion ($3\sigma_{FR}$, $3\sigma_F$, $3\sigma_R$) at the same point. The value of the mean error is dependent on the zero error line location. For convenience, we represent the zero error line as being located halfway between the extreme 3-sigma boundaries ($-3\sigma_F$ and $+3\sigma_R$) for the two worst-case test points measured along the entire range of axis travel, which is represented as a 3-D projection passing obliquely into the page. The dotted lines

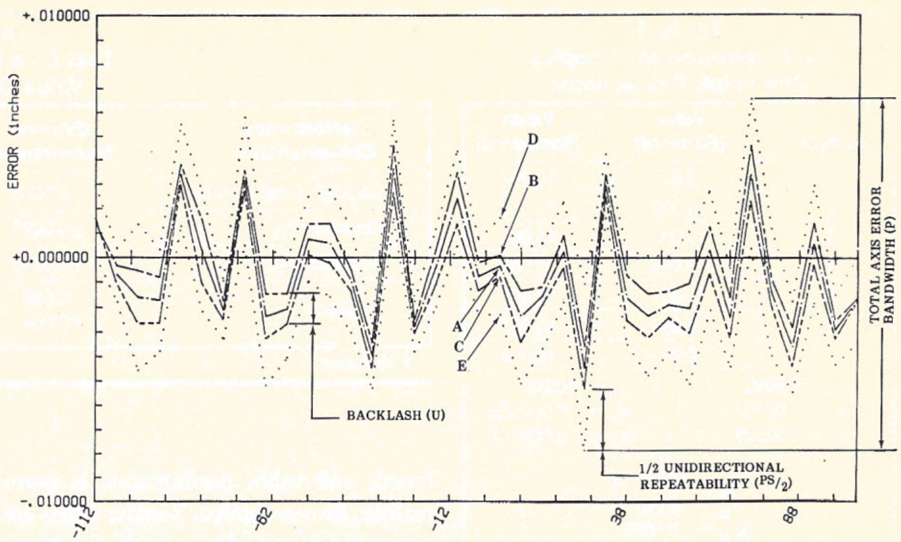

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Figure 4. Total position error bandwidth for an axis encompasses the extreme 3-sigma boundaries for the two worst-case test points measured along the entire range of axis travel.

of the 3-D projection roughly correspond to the extreme 3-sigma boundaries shown in the positioning plot of Figure 4. For further clarification, the average, forward, and reverse mean errors [(A), (B), (C)] as well as the extreme 3-sigma boundaries [(D), (E)] are indicated.

The NMBTA recommendation for bidirectional measurements calls for "normalized" results of both forward and re-

Table 1
Test Measurement Samples
One Point, Bidirectional

Sample	Value (Forward)	Value (Backward)
1	9.998	10.002
2	10.000	10.002
3	10.000	10.004
4	9.999	10.004
5	10.001	10.002
6	9.998	10.003
7	9.999	10.004
$\bar{X}_F = 9.9992$ $\sigma_F = 0.00103$ $3\sigma_F = 0.00309$		$\bar{X}_R = 10.003$ $\sigma_R = 0.000925$ $3\sigma_R = 0.002777$
$\bar{X}_M = 10.00114$ $\sigma_M = 0.00209$ $3\sigma_M = 0.0069$		

Table 2
Test Data Interpretation
Value Comparison

Performance Characteristics	Extreme Measurement	VDI-3144 Std.	NMBTA Std.
Backlash (Lost Motion)	0.0038	0.0038	0.0038
Repeatability_F*	±0.0015	±0.0039	±0.0039
Repeatability_R*	±0.0010	±0.0027	±0.0027
Accuracy	−0.002 +0.004	−0.0038 +0.0058	−0.0052 +0.0074

* Unidirectional

verse position measurement. As a consequence, 3-sigma boundaries are erroneously inflated by the amount of backlash or lost motion in the system, causing the final position accuracy values rendered from the measurements to be adversely affected. For this reason, we recommend the VDI 3441 standard for testing and evaluation of linear axes, since bidirectional measurements are more realistically combined, and robot performance is more realistically represented. 3-sigma values are computed separately for each direction.

To clarify, Table 1 presents seven measurement samples for a single point tested bidirectionally. Table 2 is a comparison of values given for robot performance characteristics, using various interpretations of the test data in Table 1. Clearly, robot performance characteristics based on extreme measurement values—as claimed by many robot vendors—is not conservative.

This is Part I of a two-part article. Part II will focus on robot error sources and error components, along with a methodology for combining dissimilar error components to obtain overall 3-D position accuracy specifications.

Albert J. Sturm is Manager of Robotic Engineering and **Ivor Matz** is an Engineering Writer for CIMCORP Inc., formerly GCA Corporation/Industrial Systems Group.

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Beacon-Referenced Dead Reckoning: A Versatile Guidance System

R. Rodion Rathbone
Robert A. Valley, Jr.
Peter J. Kindlmann
Sencar Company
32 Meadow Wood Road
Branford, CT 06405

Efforts to escape the constraints of rails or other mechanically constraining tracks in industrial automated guided vehicle (AGV) systems have produced the optical stripe- and wire-guided vehicles now used in offices, service environments, and heavy industry. Both systems provide some autonomy in the form of branching pathways and controlled stops, but they remain tied to physical tracks in the floor. On the other hand, vehicle guidance attempts based on current machine vision capabilities have led to complexities in directing vehicles through new and unfamiliar environments. Such systems necessarily have large computing overheads. They are also vulnerable to lighting changes and movement in the environment, problems that have kept them from becoming commercially feasible.

At Sencar we have developed a navigation system that requires no physical track, that obviates expensive image analysis and path planning, and that eliminates the high cost of planning and installing wire or reflective stripe guide paths. It combines a sophisticated dead reckoning system with a set of infrared beacons that provide a fixed reference frame while also carrying communications to the vehicle. The network of intended paths is programmed into the guidance system by manually steering the vehicle over all desired routes.

Our design goal was a versatile vehicle—easy to teach, amenable to path modification, highly reliable, and inexpensive.

Later, under autonomous operation, the vehicle will precisely duplicate these paths on request, using the fixed beacons to verify accuracy. Since all routes are stored within the vehicle's memory, branching and joining paths may be added at any time by driving the vehicle along the added routes. All information, old and new, can be electronically transferred to other vehicles. Storing the entire network in each vehicle permits special maneuvers such as obstacle avoidance.

DESIGN CONCEPTS

Our design goal was a versatile vehicle—one that could be taught easily and whose routes could be modified quickly, all the while maintaining high reliability. We also felt that to make it eligible for a wide range of applications, equipping a vehicle with our guidance system should add no more than $2500 to its manufactured cost.

Versatility implies significant reduction in the time, effort, and cost of installing and altering vehicle routes. Laying down wire paths and control points for a wire-guided system accounts for much of its cost. Detailed engineering drawings must be prepared with considerations for subfloor conduits and beams. Such planning is essential because of the substantial price of re-laying or altering a wire buried in concrete.

Optical stripe systems simplify the installation process but leave the track vul-

nerable to damage by wear and cleaning. Re-striping about every six months in moderate traffic areas is recommended for one commercial system (about $1.75/ft). Mimicking of the track can also be a problem: vehicles guided by fluorescent stripes have been known to follow employees' tracked-in salt footprints during the winter months.

Installation is simple; system setup can be left in the hands of a technically oriented user. Beacons are clipped to the ceiling, to posts overhead, or anywhere else in the vicinity of the desired vehicle path. The operator then drives the vehicle along its route, recording stops and docking maneuvers along the way. If a path must be changed, the vehicle is driven back to the last acceptable position and conducted over the revised path. Branches are entered in a similar fashion, retaining the previous path and adding a new path as a branch.

The steering commands can be envisioned as a series of curved arcs (Figure 1). As the vehicle is driven, the guidance system sequentially records each section and the positions of all visible beacons. Beacon positions verify the correct orientation of the sections, allowing the vehicle to accommodate arbitrary beacon locations such as those temporarily obscured by obstacles. Path accuracy is checked by using different beacons at different times, or by waiting until an appropriate beacon comes into view.

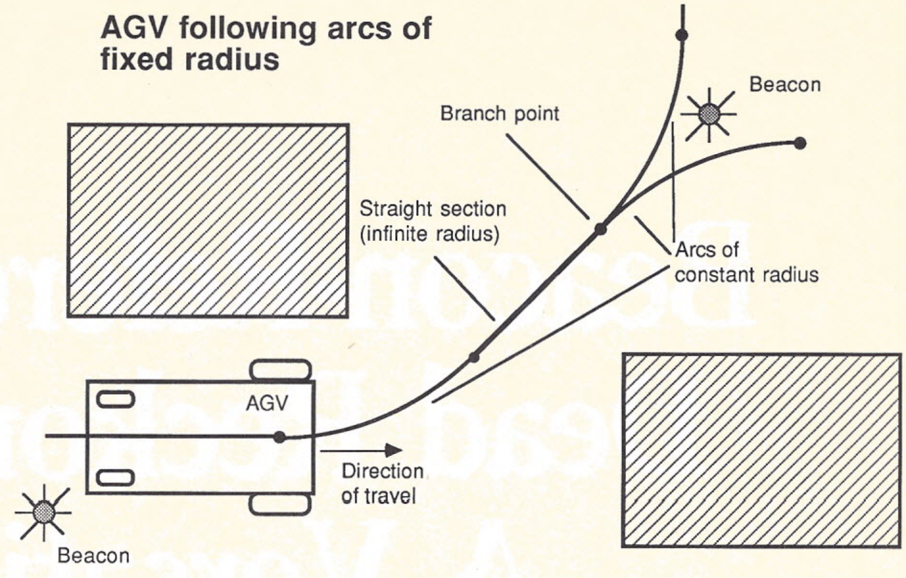

Figure 1. The vehicle's steering commands can be envisioned as a series of curved arcs.

This approach differs from more conventional beacon-guided systems. Some track directly from an active or a reflective beacon, using beam angle as part of a servocontrol loop for steering; these require careful planning of beacon placement and must stop the vehicle if the beam is interrupted.

They also require careful site planning,

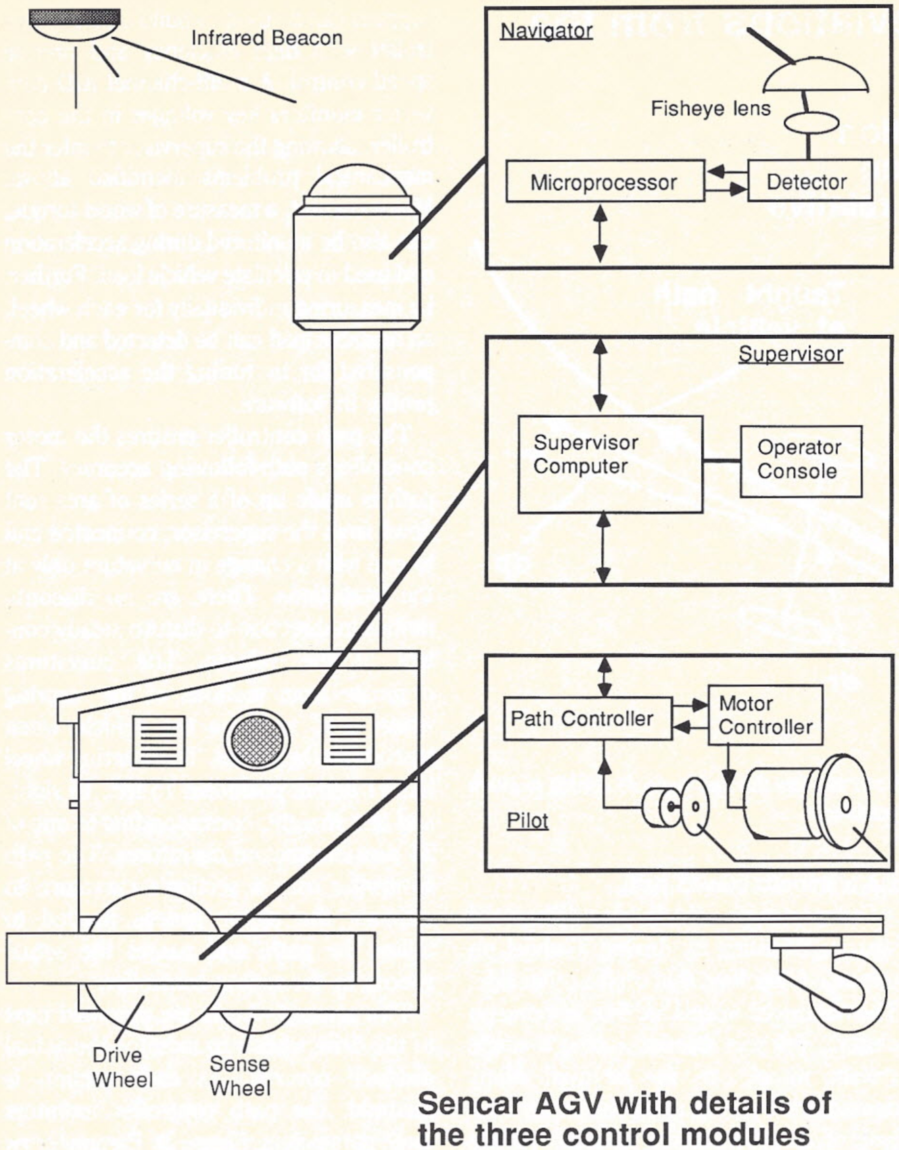

Figure 2. To simplify the design task, allow routine self-testing, and ensure ease of maintenance, the guidance system was divided into four functional units: beacons, navigator, supervisor, and pilot.

and constrain each vehicle to an externally constructed "visual track" rather than to a memorized and modifiable path. The guidance system lacks the autonomy needed for course changes and obstacle avoidance maneuvers. Other systems use multiple beacons to determine the position of the vehicle by triangulation, retaining some autonomy, but remaining dependent on frequent and precise determination of the angle to multiple beacons. They suffer from imprecision if the beacons are at some distance, and they require some means of specifying the desired path.

IMPLEMENTATION

To simplify the design task, allow routine self-testing, and ensure ease of maintenance, our guidance system was divided into four functional units. The location of the modules on our prototype vehicle is shown in Figure 2:

- Beacons—the absolute position framework
- Navigator—the beacon locating module (patent pending)
- Supervisor—the supervisory computer
- Pilot—the steering and dead reckoning module

Communication between modules passes over RS-232 serial links. Information from each beacon consists of its code and any messages for the vehicles from a central scheduler. The navigator returns communication through its own beacon, reporting beacon positions and movements of beacons it was tracking to the supervisor. The supervisor sends steering commands over its link to the pilot, which returns progress updates. Signals from obstacle detection circuits are passed directly to the pilot for immediate action by the motor control and then relayed to the supervisor.

Beacons. The beacons are similar in function, power level, and size to a television remote control, operating in the near-infrared (880-950 nm) range. Semiconductor emitters and receivers are more efficient in this region and less subject to attenuation by smoke and airborne dust. The beacons transmit serial pulse trains with check bits and unique identification numbers. Our prototypes use burst rates of 4800 to 9600 baud, although higher rates are possible. Pulse shape and specific infrared wavelength distinguish the beacons from office and plant floor environments. The beacons are clipped or stapled to ceilings, or mounted on poles or partitions. They are powered along low-voltage wiring, with up to 50 or more beacons placed along a particular wire run. The same pair of wires carries data during communication with the vehicles.

Navigator. The navigator is the key to the guidance system's reliability and has the most demanding specifications of all the components; it must locate beacons over an entire hemisphere and identify them from as far away as 30 feet in diverse lighting conditions. Light from the beacons is captured by a 180-degree fish-eye lens and focused on a two-dimensional detecting array that determines each beacon's location and identification code. The fish-eye lens eliminates any need for moving parts, and near-infrared light at moderate image resolution allows us to use a simple, large plastic lens. All fish-eye lenses introduce substantial light loss, which demands very sensitive detection circuitry whose performance is ultimately limited by thermal noise (the noise produced by a completely dark detector). Detection of distant beacons is also complicated by much brighter overhead beacons that tend to blind the navigator. (The ratio of bright to dim beacon signals can limit the practical range of the navigator.) In our prototype, the dynamic range (overhead to distant beacons) is 60 dB (1000:1), a ten-

Diagram of vehicle deviations from the taught path

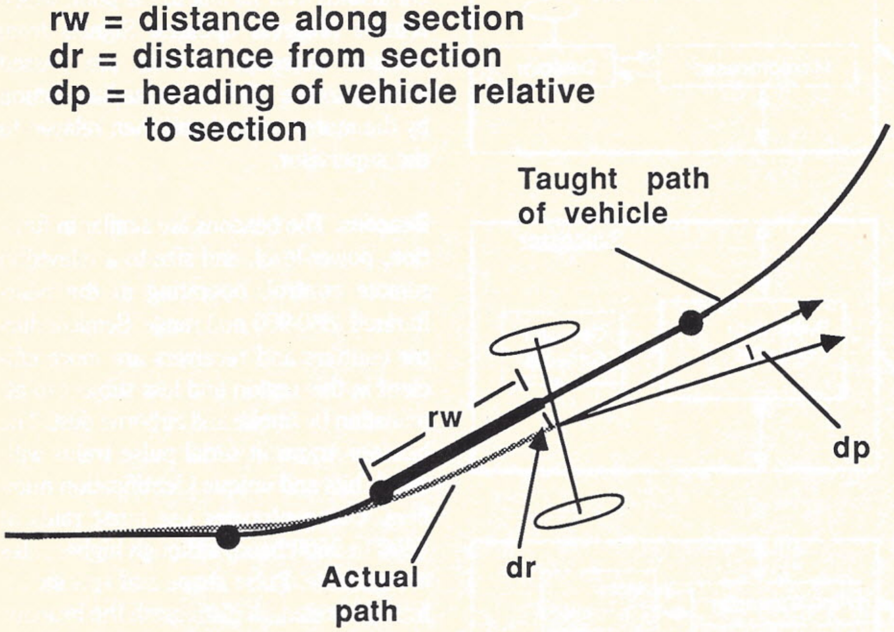

Figure 3. The path controller uses a section's curvature to estimate the motor speeds needed to follow the path and passes the actual speeds to the motor controller.

fold improvement over typical low-noise television cameras.

The detector's electronics feed a Z-8 based microcontroller programmed in C, with 32K ROM. This program controls the detection circuitry, records beacon locations, and keeps track of beacon movement as well as communications from the beacons. It communicates with the supervisor over an on-chip serial port and also controls return communications and self-testing through the navigator's own beacon. The first prototype's detector resolution provided vehicle position accuracy of 3 inches for beacons 8 feet off the ground. Resolutions of ¾ inches or better are readily obtainable using commercially available components.

Pilot. The pilot controls the movement of the vehicle, and has intelligence that allows travel during periods when no beacons are in sight. It was designed to give the vehicle a comfortable "feel" when steered by the operator and to work smoothly from the same set of commands when under automatic control. Its two main submodules are the motor controller that receives motor speed commands and regulates power, and the path controller that watches position change relative to the floor and verifies that the vehicle is following a smooth curved path.

Our prototype vehicle uses differential steering—turning by driving a wheel on one side faster than that on the other side. The nondriven wheels are free to swing on casters. Tricycle steering, using a single steered wheel, can also be used. Many demands are placed upon the motor control of a differentially steered vehicle operating independently of a track. Limited battery energy, along with the necessary electronics, requires maximum efficiency of the controller if the vehicle is to operate a complete shift without recharge. Differential steering, while simplifying the mechanical design, requires that each wheel be controlled accurately over a wide range of forward and reverse speeds. Unbalanced or heavy loads must also be detected and compensated for, since they upset the dynamics of a vehicle and subject the motors to unusual loads. By monitoring brush wear and motor heat and detecting dirt accumulation on the sensing wheels, the pilot provides maintenance checks for the supervisor that, if overlooked, could lead to unplanned downtime.

Recent advances in MOS field effect transistors have simplified their inclusion in the controller circuitry. The advantages these devices provide in switching power supplies can be used to build a motor controller with high efficiency and precise speed control. A multi-channel A/D converter monitors key voltages in the controller, allowing the supervisor to infer the mechanical problems identified above. Motor current, a measure of wheel torque, can also be monitored during acceleration and used to calculate vehicle load. Further, by measuring individually for each wheel, an unstable load can be detected and compensated for by tuning the acceleration profile in software.

The path controller ensures the motor controller's path-following accuracy. The path is made up of a series of arcs sent down from the supervisor, connected end to end with a change in curvature only at the transitions. There are no discontinuities in direction to disturb steady control of the vehicle. The curvatures originate from motions of the steering wheel used to drive the vehicle when teaching it the routes. The steering wheel has 31 detent positions: 15 left, 15 right, and one straight, corresponding to one of 31 possible section curvatures. The path controller uses a section's curvature to estimate the motor speeds needed to follow the path, and passes the actual speeds to the motor controller.

Two sensing wheels are mounted next to the drive wheels to monitor the actual distance covered. As each section is followed, the path controller monitors three parameters (Figure 3). Parameter **rw** indicates how far along the section the vehicle has traveled, **dr** is the position error indicating the vehicle's deviation from the taught section, and **dp** indicates the vehicle's misalignment from the current section. The two error variables **dr** and **dp** are used to tune the motor speeds, keeping the vehicle precisely on path. The distance variable **rw** and direction error **dp** are sent to the supervisor so that it can check them against data from the navigator.

Position data is critical to the pilot's performance. Drive wheels ought not be used to measure distance since their slippage introduces substantial errors. Independent sensing wheels avoid slippage errors, but are still subject to wear or dirt pickup that changes their effective diameter. Accordingly, the path controller keeps an adjustment factor for each wheel, calculated by the supervisor and based on prior course corrections. This is an integer ratio of actual counts per unit distance from a shaft

encoder vs. ideal counts/unit distance. The actual counts are converted to ideal counts using this ratio. Any round off in the conversion is carried over to the next conversion to prevent accumulation.

Supervisor. The top administrative level of vehicle guidance—coordinating other modules, record keeping, outside communications, and task planning—is handled by the supervisor. It provides the long-term storage of the path network (in EEPROM) and selects the sequence of path sections needed to get to the next destination, sending them to the pilot, monitoring the pilot's progress along them, and sending more sections as needed. The supervisor coordinates the vehicle's behavior at doorways and intersections, based on signals from the beacon communications link; it also handles requests entered at the operator console and handles the range of special maneuvers involved in docking and obstacle avoidance.

The supervisor's most important task is to monitor and correct errors in the pilot's path orientation. The path sections are referenced to the floor through the sensing wheels' movement. Each section is oriented with respect to the previous section, and if the sensing wheels measure distance without error, each path will be laid out properly. Small errors, however, are inevitable. Picturing the vehicle on a straight section, as in Figure 4, if the left sensing wheel goes over an obstacle or

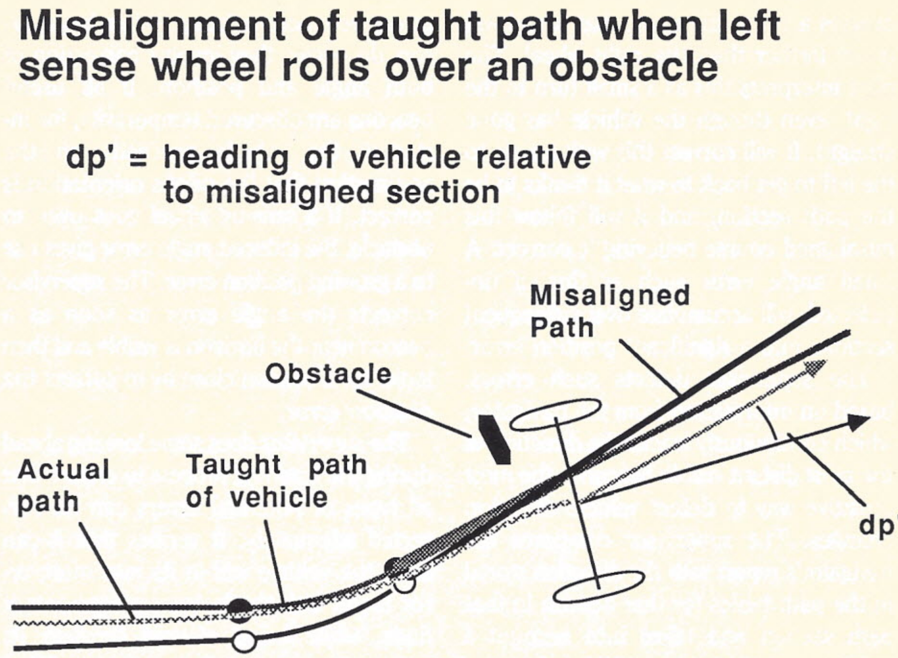

Figure 4. When a sensing wheel goes over an obstacle, it travels farther than the other wheel. The pilot interprets this information as a small turn and attempts to correct the course with a turn in the opposite direction, causing a course misalignment.

crosses a rut in the floor, that wheel will travel farther than the right wheel. The pilot interprets this as a small turn to the right, even though the vehicle has gone straight. It will correct this with a turn to the left to get back to what it thinks to be the path section, and it will follow this misaligned course believing it correct. A small angle error such as this, if undetected, will accumulate over subsequent sections into a significant position error.

The supervisor detects such errors, based on information from the navigator, which continuously tracks the direction of the most distant visible beacon— the most sensitive way to detect vehicle direction changes. The supervisor compares the navigator's report with the direction stored in the path tables for that beacon in that path section and takes into account a number of variables: the pilot's vehicle-to-path angle, the distance traveled on the current section, and the curvature of that section. If the supervisor decides the discrepancy is significant, it will subtract out the misalignment from the vehicle-to-path angle, **dp**, thus correcting the pilot's orientation.

These small corrections prevent larger errors from accumulating. When larger errors do occur, they involve correction of both angle and position. If all useful beacons are obscured temporarily, for instance, the vehicle proceeds on the assumption that the pilot's orientation is correct. If a sensing wheel goes over an obstacle, the induced angle error gives rise to a growing position error. The supervisor corrects the angle error as soon as a beacon near the horizon is visible and then looks for a beacon close by to correct the position error.

The supervisor does some looking ahead during the teaching process to ensure that all types of potential errors can be corrected adequately. It verifies that it can keep the vehicle within its maximum error limits with the beacon placements it finds, while being steered through its routes. The error limits can be modified by the operator. Some critical areas will need tighter tolerances, and the vehicle may be required to stop if it can not verify that it is within them.

CONCLUSION

We have described a system that ties vehicle navigation to a framework of beacons whose placement is quite flexible in that they need not be visible at all times and at all points along the route. The layout of the workplace and the vehicle's intended functions will define the choice of path, unburdened by structural considerations and the permanence of laying a wire in concrete. The software for reconciling the dead reckoning from sensing wheel data with the absolute coordinate grid provided by the beacons is a fundamental research area that continues to evolve. Refinements of system communications protocols, multiple vehicle coordination, and obstacle avoidance maneuvers will depend more specifically on the context of particular applications.

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Excellent	Good	Fair

Making Robots Count

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Numerous attempts have been made in the past to accurately assess the cost benefits of having a robot on the shop floor. Most robot applications, when cost justified, are evaluated on the basis of the number of employees directly replaced by the robot. Other benefits, while having a recognizable value, have been overlooked as too intangible to assign dollar worth. Ellison Robotics has developed an extensive financial model that allows current or potential robot users to put a value on these intangible benefits, as well as to account for cash flows over the life of the robot system. The model incorporates costs and savings, adjusts them for inflation, and evaluates the system by three methods: payback in years, net present value, and return on investment.

Before undertaking an extensive analysis of a robot application to see if it is cost justified, the user would be well-advised to use some rough estimates to assess the feasibility of the application. Ellison's payback tables are a handy tool for this procedure. Before explaining financial models and the payback tables, let us review a few basics of the costs and benefits of robotic applications.

COSTS AND SAVINGS

The costs associated with a robot system are for the robot and controller, support equipment (feeders, end effectors, fixturing, etc.), engineering, installation, and training (soft costs). These can be estimated based upon current price lists and/or past experience, or by using some other standard, as will be illustrated later.

Even more important than a robotic system's initial costs are the savings to be realized. These savings can be broken into four categories: personnel, productivity, tax, and miscellaneous (see the section on using the spreadsheet). Most manufacturers expect a capital project to have a simple payback in two years or less. This benchmark will be used in identifying cost-effective applications for robots throughout this article. We will now consider means of identifying cost-effective uses of robots.

Table 1
Estimated Hourly Savings Necessary for (N) Payback

(Estimated savings = cost/52 weeks × 40 hours × years/shifts)

1½-Year Payback

Robot System Cost (000s)	1 Shift	2 Shifts	3 Shifts
$360	$115	$58	$39
330	105	53	35
300	96	48	32
280	90	45	30
260	83	42	28
240	77	39	26
220	71	35	24
200	65	32	21
180	58	29	19
160	51	26	17
140	45	22	15
120	39	19	13
100	33	16	11
80	26	13	9
60	19	10	6

2-Year Payback

Robot System Cost (000s)	1 Shift	2 Shifts	3 Shifts
$360	$87	$43	$29
330	79	40	26
300	72	36	24
280	67	34	22
260	63	31	21
240	58	29	19
220	53	26	17
200	48	24	16
180	43	22	14
160	39	19	13
140	34	17	11
120	29	14	10
100	24	12	8
80	19	10	6
60	14	7	5

Three-Year Payback: ½ of the 1½-year payback amount
Four-Year Payback: ½ of the 2-year payback amount

ESTIMATED HOURLY SAVINGS

Table 1 gives the estimated hourly savings needed to justify a robot purchase, given a system price, the number of shifts worked, and the desired payback. The following is an example of how to use the table.

A sales representative estimates that a welding robot system would cost about $120,000. The shop has two work shifts. To achieve a 1½-year payback, the robot must save the customer about $19 per hour; for a two-year payback, it must save $14 per hour. Looking at the potential savings, the manufacturing manager estimates that the robot will eliminate one worker per shift at $10 per hour + employee benefits at $6.50 per hour (65 percent × $10/hr.) + reduce rejects at $1 per hour (one fewer per hour) = total hourly savings of $17. The system can thus be easily justified under a two-year payback, but it does not meet a 1½-year payback. Further consideration of a robot application is in order.

The table can be used in the other direction, too. Say the manufacturing manager is not sure how much he should spend on a robot. After looking at his operations, he determines that the possible savings from a one-shift operation would total about $14 per hour. The two-year payback table indicates that these savings will justify buying a $60,000 system. There is not much need for further consideration if the required system would cost $120,000,

SAMPLE SPREADSHEET

1	**A Financial Feasibility Spreadsheet For Robot Applications**	
2		
3	**COSTS**	
4		
5	BUY-	
6	Base Price of Robot with Controller	$110,000
7	Support Equipment (feeders, end effectors, etc.)	20,000
8	System Design, Coordination, and Documentation	35,000
9	Training, Programming, and On-Site Assistance	0
10	Provide Floor Space and Install	0
11	Periodic Costs: Finance + Maintenance + Training =	
12	(not included Year 1	1000
13	in total cost 2	3000
14	year 0) 3	500
15	4	6000
16	5	500
17	(Less One Time Savings-ITC, Government Grants, etc.)	12,000
18	TOTAL COST YEAR 0	$153,000
19		
20	LEASE/LOAN-	
21	Amount Being Financed	$100,000
22	Interest Rate	17%
23	Life of Lease/Loan	5 yr.
24	Estimated Annual Payments*	$31,256
25	*Must be calculated by hand	
26		
27		
28	**SAVINGS**	
29		
30	**PERSONNEL** (based upon number of people displaced by robot)	
31	Regular Wages (annual)	
32	Direct Labor	$35,000
33	Supervisory Labor	5000
34	Indirect Labor	500
35	Shift Differential	0
36	Savings	40,500
37	Overtime Wages	0
38	Employee Benefits	
39	B. Legally Required (as a % of the base wage)	10%
40	C. Pension and Insurance " "	30%
41	D. Paid Rest and Lunch Periods " "	0%
42	E. Vacations, Sick and Personal Days " "	0%
43	F. Profit Sharing, Christmas, and other Bonuses " "	0%
44	Savings	16,200
45	Turnover	
46	Recruiting Costs (per employee)	50
47	Training Costs	150
48	Occurrences per Year	0.50
49	Savings	100
50	Tools and Equipment (annual)	
51	Safety and Other Equipment	150
52	Handheld Tools	300
53	Savings	450
54	Overhead Allocation (if based upon labor charges)	0
55	TOTAL PERSONNEL SAVINGS (fully loaded burden rate)	$57,250
56		
57	**PRODUCTIVITY** (based upon annual changes in units)	
58	Increase in Unit Output	
59	Old Production Level (enter at least "1")	$10,000
60	New Production Level (enter at least "1")	10,500
61	Savings	$2,025
62	Quality/Yield	
63	Decrease in Discarded Rejects (in units per year)	500
64	Cost of Discards (per unit)	1.10
65	Decrease in Reworked Rejects (per unit)	1000
66	Cost of Rework	0.75
67	Decrease in Rework Inventory	500
68	Carrying Cost of Inventory	0.27
69	Value of Freed Floor Space	100
70	Decrease in Quality Control Inspection Costs	5000
71	Savings	6535
72	Decrease in Consumable Material	
73	Material Saved (in units per year)	150
74	Cost of Material (per unit)	0.30
75	Savings	45
76	Retooling	
77	Labor for Retooling (per event)	500
78	Percent Saved by Robot	15%
79	Equipment for Retooling (per event)	5000
80	Percent Saved by Robot	30%
81	Occurrences of Retooling per Year	3
82	Savings	4725
83	TOTAL PRODUCTIVITY SAVINGS	$13,330
84		
85	**TAX EFFECTS/GOVERNMENT GRANTS**	
86	Investment Tax Credit (net out from cost above)	
87	Tax Savings from Depreciation Year 1	250
88	2	300
89	(not included in year 0 savings) 3	150
90	4	125
91	5	100
92	Government Grants (if one time, net out from cost above)	100
93	Tax Bracket	40%
94	TOTAL TAX SAVINGS	$100
95		
96	**MISCELLANEOUS**	
97	Decrease in Work in Process Inventory (units per year)	1000
98	Carrying Costs of Inventory (per unit)	0.27
99	Value of Freed Floor Space (total dollars per year)	150
100	Savings	420
101	Decrease in Raw Materials Inventory	2000
102	Carrying Costs of Inventory (per unit)	0.27
103	Value of Freed Floor Space (total dollars per year)	100
104	Savings	640
105	Decreases in Finished Goods Inventory	2500
106	Carrying Costs of Inventory (per unit)	0.27
107	Value of Freed Floor Space (total dollars per year)	450
108	Savings	1125
109	Other Freed Floor Space	100
110	Warranty Costs per Year	1500
111	Percent Saved by Increased Quality	75%
112	Savings	1125
113	Other Annual Savings (specify)	350
114	Part eliminated due to product redesign	
115		
116		
117	TOTAL MISCELLANEOUS SAVINGS	$3660
118		
119	TOTAL SAVINGS	$74,340
120		******
121	OTHER INFORMATION	
122	Expected Rate of Return of Projects	0.12
123	Rate of Inflation during Period of Evaluation (per year)	0.04
124	Project Life in Years	5
125	Estimated Salvage Value of System at End of Project Life	$10,000
126	**	*****

unless the manager accepts a greater payback period, or wants to expand to multiple shifts.

FINANCIAL SPREADSHEET

After identifying possible robot applications and determining that a robot system can be cost justified, it is reasonable to do a more detailed analysis of the financial benefits. This can be done by using Ellison's Financial Feasibility Spreadsheet for Robotic Applications, a sample of which accompanies this article. The spreadsheet can also be used for a simple analysis (reduction of direct labor only).

The spreadsheet is divided into two sections, data entry and financial analysis. In the data entry section, the user inputs costs and savings information, which is then combined in determining the benefit of the robot. This benefit is shown in the financial analysis section, where the cash flows are shown for each year, adjusted for inflation, and then evaluated for payback in years, net present value, and return on investment.

Costs. The costs associated with the installation and operation of a robot system are often easier to identify than the savings. They are: base price of robot and controller; support equipment, part feeders,

Table 2
Estimates of System Cost

Application	Support Equipment	Soft Costs
Welding	95%	50%
Material Handling	40%	50%
Machine Loading	35%	45%
Paint Spraying	20%	20%
Assembly	110%	75%
Machining	35%	40%
Average	45%	40%

Adapted from, *Economist Intelligence Report 135, Chips in Industry, 1982*

Table 3
Employee Benefit Cost
Average Values by Nationwide Industry Group for 1984
(as percent of base wages)

	A	B	C	D	E	F
Total, all manufacturing	63	18	23	3	15	5
Manufacture of						
Food, Beverages	69	21	26	3	14	4
Paper, Lumber, Furniture	58	19	18	3	14	4
Chemicals and products	65	15	23	4	18	5
Rubber, Leather, Plastics	62	21	22	2	14	2
Stone, Clay, Glass	68	20	26	4	16	2
Fabricated Metal	69	20	25	6	15	4
Machinery	60	16	20	4	16	5
Transportation equipment	65	17	24	4	17	4
Instruments and Miscellaneous	56	16	17	2	14	7
Total, all firms						
10% paid more than	94					
25% paid more than	75					
50% paid more than	56					
75% paid more than	42					
90% paid more than	31					

A = Total, all employee benefits
B = Legally required payments
C = Pension, insurance, and other negotiated payments
D = Paid rest periods, lunch periods, etc.
E = Payments for time not worked (vacations, etc.)
F = Profit sharing and bonuses

Adapted from *Employee Benefits 1984, U.S. Chamber of Commerce*

and end effectors; system design, coordination, and documentation; training, programming, and on-site assistance; and floor space and installation. These costs, if not known, can be estimated by using the base price of the robot and Table 2.

The values in this table are expressed as a percent of the base price of the robot with controller. Example: Welding robot and controller cost: \$50,000; support equipment cost = 95 percent × \$50,000 = \$47,500; soft costs = 50 percent × \$50,000 = \$25,000; total system cost = \$50,000 + 47,500 + 25,000 = \$122,500.

In addition to these costs there are periodic costs that include financing, maintenance, and training costs. Financing costs can be balloon or other irregular lump sum payments. Maintenance costs can take the form of parts scheduled for replacement at irregular intervals. Training costs can be incurred at various points in the life of the system.

Savings. The spreadsheet differs from most other financial evaluations of robotic

FINANCIAL ANALYSIS

1							
2	**Projected Cash Flows Over The Life of Robot System**						
3							
4	YEAR	0	1	2	3	4	5
5							
6	COSTS						
7	Cost Year 0	$53,000	$0	$0	$0	$0	$0
8	Periodic Cost*	0	1040	3245	562	7019	608
9	Lease/Loan Payments	0	31,256	31,256	31,256	31,256	31,256
10							
11							
12	SAVINGS						
13	Personnel Savings*	0	59,540	61,922	64,398	66,974	69,653
14	Productivity Savings*	0	13,863	14,418	14,994	15,594	16,218
15	Tax Savings	0	250	280	190	175	160
16	Miscellaneous Savings*	0	3806	3959	4117	4282	4453
17	Salvage Value	0	0	0	0	0	10,000
18							
19	Discount Factor for NPV	1.00	0.89	0.80	0.71	0.64	0.57
20	Inflation Factor	1.00	1.04	1.08	1.12	1.17	1.22
21	* Subject to inflation factor						
22	NET CASH FLOWS	($53,000)	$45,164	$46,077	$51,881	$46,750	$68,620
23							
24							
25	EVALUATION:						
26							
27	Payback in Years:	1.15 Years					
28	Net Present Value:	$130,904					
29	Return on Investment†	0.85685× 100 = %					
30	†Estimate ROI until "Net" below approaches zero						
31							
32			D.C.F.:	$53,000			
33			Net:	$0			
34							

systems in that it permits the user to put a price on intangible benefits. Savings are broken into four sections: **personnel, productivity, tax,** and **miscellaneous.**

In the **personnel** savings section, the model addresses standard savings, such as reduction in direct labor, as well as other savings that include reduction of indirect and supervisory labor, employee turnover, cost of equipping employees, and cost of employee benefits, such as sick days, vacation, rest periods, etc. (known as the burden rate), that can cost from 22 to 186 percent of the hourly wages. The 1984 average for manufacturing firms was 64 percent (Table 3). Indirect labor takes into account the robotic system's ability to perform functions such as parts transfer from one workstation to another. A reduction in the number of workers to be supervised brings a corresponding reduction in supervisory labor. Jobs that are particularly hazardous or undesirable can cause a high personnel turnover, a problem robots eliminate. Further, a robotic system obviates the need for hand tools and equipment.

In the **productivity** savings section, the model treats benefits from increases in production and product quality, decreases in the use of consumable material, and decreased expenses for retooling. An increase in the production level (output) in changing from a manual system to flexible automation saves on the additional wages that would be paid to human workers to increase their level of output. Since robots outperform humans in terms of precision and regularity, an automated line produces fewer rejected units. Greater precision also means the robot uses less material in the manufacturing process. Finally, the robot's reprogrammability can decrease retooling expenses.

Tax savings come from the Investment Tax Credit, which represents a direct reduction of the purchasing firm's tax bill and amounts to 10 percent of the purchase price. Other government and military grants are also available to firms that buy new equipment in order to reduce production costs. Depreciation, a non-cash expense, is also taken into account.

Miscellaneous savings included are for decreased inventory levels, decreased use of floor space, and decreased warranty costs. These savings are more common to multiple robot systems, but may have a significant value in single installations as well.

Financial Analysis. The **financial analysis** section shows the cash flows for the robot system, based upon the entries made in the data entry section. It includes the project's payback in years, net present value, and return on investment, in recognition of the fact that the user might have different preferences in evaluation methods. The spreadsheet is set up so that the user can conduct a variety of "what if" scenarios by varying the factors in the data entry section. This is an excellent way to test the robot system's sensitivity to different costs and savings.

At this time, industry appears to base the majority of its robotic investment decisions on a combination of factors. While the financial aspects of a robotic application might currently be assigned only secondary importance, as industry acquires more experience with robots monetary considerations will become increasingly important and financial models, such as the one outlined here, will make the evaluation of financial factors easier to manage in the future.

Marcus Abundis is a consultant for Ellison Robotics.

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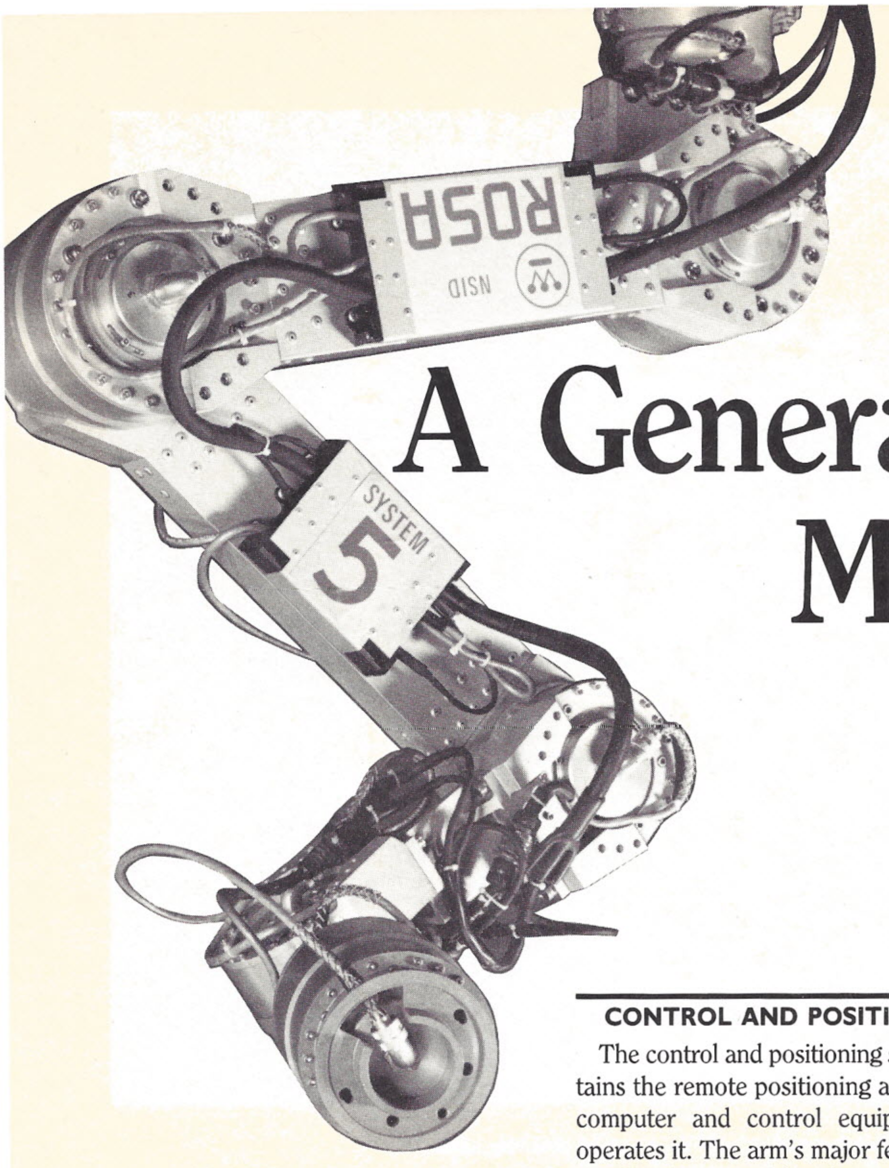

ROSA, A General-Purpose Manipulator

Daniel J. Statile
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ROSA, Remotely Operated Service Arm, is a product of experience in hazardous environment maintenance and advanced automated system technology. The technology is now four years old and continues to provide new solutions to long-term service problems. ROSA is a general-purpose multiple-axis lightweight arm capable of preprogrammed, joystick, or teach and repeat motion (Photo 1). The arm is designed to operate in hazardous, unstructured environments, controlled from a distance of up to 600 feet.

ROSA incorporates three essential elements:

- The control and positioning system
- The base system
- The end effector system

This article will focus on the control and positioning system and its applications.

Photo 1. The Remotely Operated Service Arm, ROSA, is designed for use in hazardous, unstructured environments such as nuclear power plants.

CONTROL AND POSITIONING

The control and positioning system contains the remote positioning arm and the computer and control equipment that operates it. The arm's major features are:

- Six degrees of freedom
- Lightweight (120 lb.)
- 6-ft reach
- 65-lb. payload
- 0.25-in. tip accuracy
- 6 in./sec. tip velocity
- All-electric, modular actuators
- Fail-safe brake
- Absolute position feedback

The arm's greatest attributes are its flexibility, reliability, and portability. In its present configuration, the arm consists of six actuators that permit near-anthropomorphic motion. Each actuator is a self-contained (modular) unit with a motor, gear train, brake, and position feedback elements. The modular design was created for two primary reasons: the modular actuator allows us to create new arm configurations for rapid deployment with ease of integration; and arm availability is increased with the ease of actuator replacement in the field.

The arm configuration incorporates two actuator sizes, 3000 in.-lb. and 6000 in.-lb. units. Three 6000 in.-lb. actuators positioned at the base end are in a roll-to-pitch-to-pitch configuration. The remaining three actuators are 3000 in.-lb. actuators in a pitch-to-yaw-to-roll configuration. This combination generates a work envelope that is essentially a hemisphere with a 5-ft radius. ROSA's actuators are all-electric, eliminating any chemistry concerns due to fluid, and they incorporate a fail-safe brake that "freezes" the arm and maintains position in the event of a power loss.

ACCURACY

A few comments on accuracy are in order here. The arm is used primarily for service in unstructured environments, and it has been demonstrated through experience that accuracy beyond 0.25 in. is more than can be cost justified for such applications. Due to tolerance stacking and other unforseen events, the world is never what is modeled on paper. Therefore, the end effectors provide the needed compliance for the majority of applications. The arm itself has a repeatability to within a couple of mils. This accuracy and repeatability, coupled with end effector compliance, has been demonstrated in numerous field applications.

The computer and control equipment

for moving the arm is part of a self-contained, transportable control station. The station in its current design operates one ROSA system, but future requirements include the operation and coordination of two arms from one controller. The control station includes the supervisory computer, the servo controller, and an operator control console containing the status panel and manual controls. The supervisory computer is the main operator interface for controlling the arm. The operator issues commands to the computer from the control console. The computer then interprets these commands and calculates the desired movement along each axis of the arm. The characteristics of the supervisory computer include:

- Multiprocessor-based. The supervisory computer uses several microprocessors operating in parallel to perform the high-speed mathematics required for moving the arm, monitoring system health, servicing the switch panel and joystick, and communicating with the servo controller.
- Operates in real time. Computations are performed instantly as they are requested. When the computer commands a move, the computer calculates the information required within 50 msec.
- Displays system health. The supervisory computer, through communications with the servo controller and the control console, employs warning lamps to alert the operator to system problems.

Signals from the supervisory computer are transmitted to the servo controller, which uses them to power the actuators and move the arm to the proper position. This control signal-to-power transition is executed at a high rate of speed, allowing smooth, continuous motion. Design characteristics of the servo controller include:

- Obtains and maintains arm position. The servo controller receives strings of joint angle commands through a data link from the supervisory computer and continuously drives the arm toward the desired angle.
- Monitors arm health. The computer in the servo controller monitors arm health (for example, a high motor current) and alerts the supervisory computer through a message on the data link connecting the two. The servo also has analog indicators to display brake current, motor current, and voltages.
- Microprocessor-based.
- Software servo loop. The servo loop can be altered simply by changing constants in the servo equation.
- Powers arm up to 600 feet away. The servo can power the arm and read the joint angles through a 600-ft-long umbilical cable. System cables are fully shielded to minimize interference over this line length.

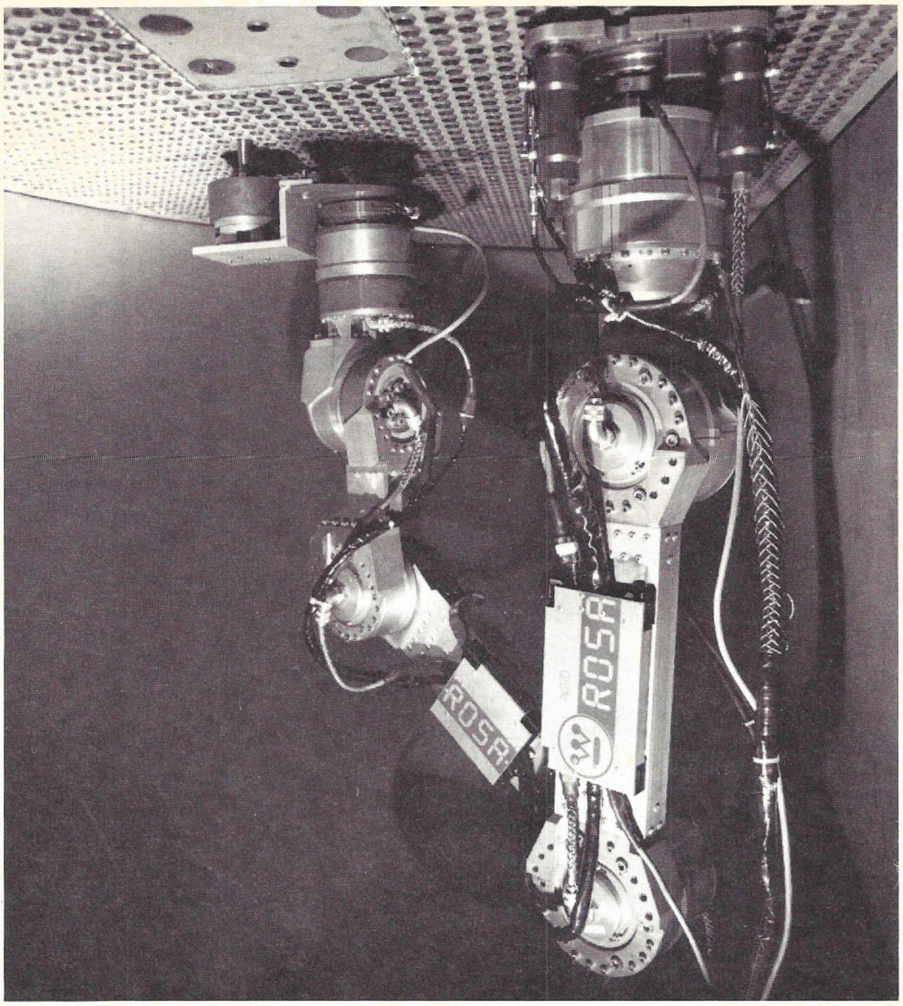

Photo 2. ROSA is shown plugging holes in a steam generator head.

The modes of operation of ROSA are basically three: automatic computer program control, teach and repeat, and joystick. In the automatic mode, ROSA's actions are dictated by a program that directs the arm through the supervisory computer. This mode is effective for large, repetitive tasks, such as steam generator tube inspection, where up to several thousand tubes must be addressed. The teach and repeat mode is appropriate for field applications such as welding, where the path and speed can be taught to the computer prior to striking an arc. And the manual mode or joystick control is useful for highly unstructured environments where teleoperation is critical. The joystick mode is also important for fine positioning of tooling after preprogrammed motion has ceased.

APPLICATIONS

Applications of ROSA are wide and varied. Essentially, it has been used to perform tasks where the environment is unacceptable for humans and for tasks that are highly repetitive in nature. ROSA can operate under water, in high-radiation fields, in caustic environments, in space, and in air.

ROSA's first job took place in a U.S. utility in February 1983 (Photo 2). The mission was to perform an upflow conversion process used to redirect the coolant flow path within a nuclear reactor. ROSA's task was to measure and plug 20 holes in the core barrel while submerged in 20 feet of heavily borated water. The arm was operated from a 600-ft distance from the

Photo 3. The arm can be operator-controlled from a trailer 600 feet away from a hazardous environment.

containment building for three and one-half continuous days (Photo 3).

Since this outing, ROSA has been at work in a variety of nuclear service roles. The predominant application is steam generator work. Westinghouse sees zero entry as: At no time throughout the duration of the job is the plane of the steam generator manway breached by any personnel. ROSA's dual-ended capability finds use from the very beginning of steam generator maintenance. The arm loads itself into the generator via a fixture attached to the flange of the manway. With its tool end attached to the loading fixture, ROSA, through preprogrammed movement, inserts its base into the tubesheet for continued operation. Once in the generator, ROSA uses end effectors to perform eddy current inspection, ultrasonic inspection, sleeving, plugging, hardrolling, tube expansion, and a variety of other operations necessary to complete the job. Westinghouse is at present completing the development of a new ROSA vessel inspection, machining, and welding system that will be improved over the existing system.

ROSA's flexibility for autonomous operation for space station applications was demonstrated recently: A structure similar to the form a space structure might take was built. In the center of this structure was a ladder. ROSA was placed at one end of the structure and given the assignment of getting to the other end of the structure. This exercise demonstrated collision avoidance, path planning, stereo vision, and mobility. ROSA, equipped with two cameras at one end, viewed the ladder, deduced the rung position, and estimated its distance. It then plotted a path through the rungs, and proceeded end over end, attaching itself to the structure, to reach its destination.

In conclusion, the ROSA system is a proven, reliable, end effector delivery or mobile tool system that is portable between sites and flexible enough to perform a multitude of tasks. Design foresight lends the arm to applications in chemical, power, and aerospace industries.

Daniel J. Statile is an Engineer with Westinghouse's Service Technology Division.

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Robotic Plasma Spraying

T.E. Barnard and **Edwin Garofalo**
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Old Bethpage, New York 11804

Engineered coatings are widely used to improve the performance of critical components by providing the surface properties best suited to their working conditions. Using engineered coatings, a designer can choose a material possessing all of the required bulk properties (e.g., strength, rigidity, weight), and enhance that material with the ideal surface properties (hardness, wear resistance, resistivity, etc.).

Many of the more technologically advanced industries are today employing engineered coatings applied by highly automated plasma spraying, a versatile process that uses a directional thermal plasma to melt powdered materials and propel them onto a substrate, where the molten particles solidify to form a coating. Playing an important role in the development of high-performance plasma-coated components is the use of sophisticated production coating equipment and controls.

At Hitemco, the coating of such critical components as aerospace turbine vanes, blades, and shrouds; orthopedic implants; and computer tape heads has been significantly enhanced by the development of a robotized plasma spraying facility. Designing the facility entailed robot selection, retrofitting core and ancillary equipment to interface with the robot and its controls, and construction of a work enclosure to house the robot. To ensure optimum coating capabilities, this effort followed stringent in-house quality standards and production criteria.

ROBOT SELECTION

Automated plasma spray coating, like other robotic production applications, requires a robot capable of making complex series of movements accurately while sequencing certain production operations. Hitemco set three additional major performance criteria:

- Accurate functioning within the spray operations environment, which is characterized by high-frequency interference and dust
- Ability to support heavy payloads (up to 55 lb.) moving at high velocities (1500 mm/sec.) through the work envelope (4 ft by 8 ft)
- Easy programming for effective interface with ancillary equipment

The requirements clearly defined, Hitemco began its robot selection by reviewing manufacturers' literature, attending trade shows, and analyzing systems in product demonstrations. The experience gained pointed up the limitations of a welding robot (in terms of both speed and operations) and ultimately led to the choice of a six-axis, articulating arm robot, Model AR-1000, manufactured by Metco, of Westbury, New York. (The decision was also influenced by the fact that Metco had supplied some of Hitemco's existing production equipment. Not only did the "one-source" supplier concept appeal; the company also foresaw a less difficult task in equipment interfacing.)

ENCLOSURE DESIGN

Streamlined operation with effective noise and dust abatement was Hitemco's primary objective for its robotic enclosure design. Requirements called for a soundproof, fully water washed and exhausted enclosure that would protect the manual work areas from the plasma process's high dB noise levels and collect excess coating materials. Accordingly, the room was constructed of vinyl-coated acoustical absorbent material. Smooth surfaces enhanced the effectiveness of the dust collection system.

The work enclosure consisted of two mirror image robot workrooms, back to back, each housing a robot, power supply, heat exchanger, water wash exhaust sys-

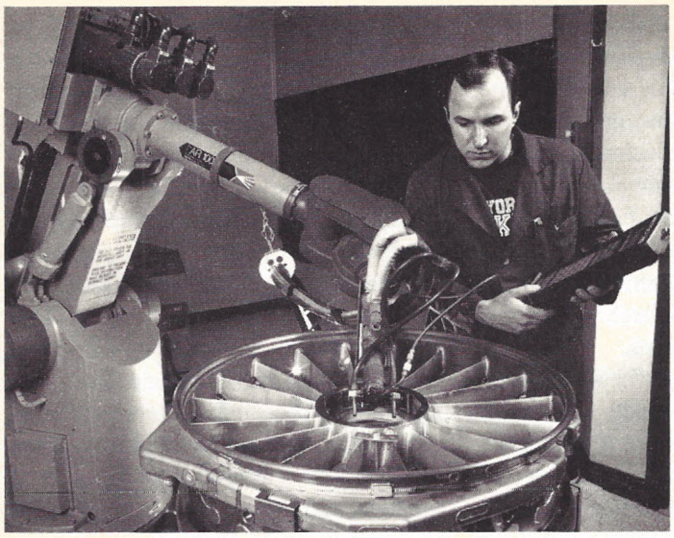

Photo 1. The spray coating program is loaded into the robot by means of a teach pendant.

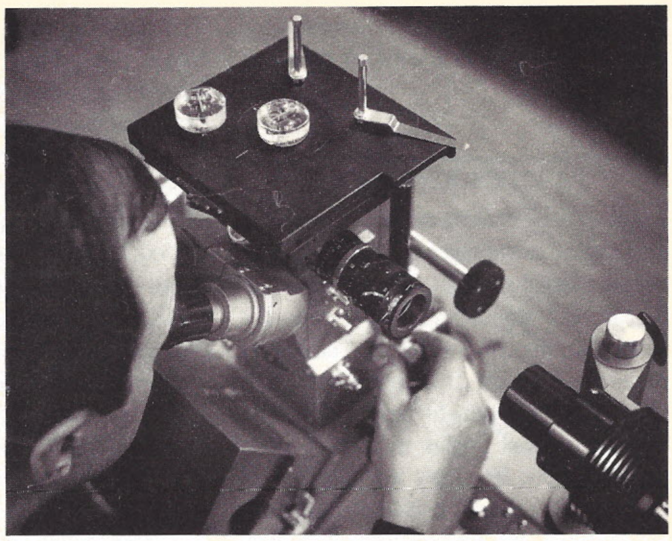

Photo 2. Representative sample coatings are produced along with the actual workpieces. These are examined metallographically in the lab, thus eliminating the need for destructive testing of the components themselves. A technician is shown conducting a visual cross section analysis.

tem, and plasma spray equipment. Wide doors with a broad workspace were provided for easy access and for positioning part manipulators. Adjacent to the entrance to each robot workroom was an anteroom for parts preparation.

A central command station from which both robots could be operated straddled the robot workrooms. The command station housed all of the controls for the robots and spray equipment. Both robot workrooms were in full view of the programmers, which proved valuable in terms of maximum safety for operators, workpieces, and equipment.

Retrofitting and Robot Interface. Coating equipment such as turntables and other workpiece presentation equipment were sized to make maximum use of the robot's work envelope. The design allowed fixturing to be precisely located relative to the robot arm according to markings on the workroom floor, where it was held in place with special brakes.

The plasma spray gun, gun and workpiece cooling equipment, exhaust system, and part manipulators were all interlocked through the system's interface unit for proper sequencing by the robot. Special fixtures for fastening each part onto a workpiece manipulator were designed to attach without tools, thus minimizing the time required to shift from one operation to another. This was an essential consideration since Hitemco's coating service is often the final stage in a manufacturer's critical path of production, affording little if any slack time.

SYSTEM OPERATION

Once the enclosure and coating equipment modifications were completed, Hitemco set out to develop computer programs for the robotic facility. Depending upon the complexity of the part being coated, the robot moves the spray gun through a sequence of positions that are coordinated with the location of the workpiece and operation of the spray system and ancillary equipment (Photo 1).

The system operates in the following manner:

1. The robot moves the plasma spray gun to a safe position.
2. The part manipulator is turned on.
3. The spray gun cooling equipment is rotated.
4. The spray gun is lit.
5. The part to be coated is preheated.
6. The robot arm moves the gun to another safe position.
7. The feeding of the coating material begins.
8. The workpiece coolers are turned on.
9. The part is coated.
10. The coating material feeder is turned off.
11. The robot arm moves the gun to another safe position.
12. The spray gun is turned off.
13. The ancillary exhaust and cooling equipment is turned off.

Throughout the program, various safe pauses allow the operator to measure the component, institute quality control checks, or load new parts. The CRT presents timely messages to advise the operator of the phase of coating in process or to give pertinent operator instructions.

INTEGRATION WITH IN-HOUSE LAB

The high costs associated with many of the components coated by Hitemco preclude the application of "destructive" evaluations to monitor coating quality. Therefore, representative sample coatings are produced along with the components. These samples are examined metallographically and compared with established standards for hardness, microstructure, oxide content, void content, bond line condition, tensile bond strength, and other physical properties (Photo 2). Stringent process controls executed by the robotic facility combined with extensive laboratory testing ensure product quality.

PERSONNEL TRAINING

To familiarize operators with the robotic flame spray operation, rigorous on-the-job training was provided. Operators were first required to demonstrate their plasma spray coating expertise and skills in formal written and performance tests. Qualified operators then participated in intensive, on-site training during the robot installation.

Finally, they participated in a week-long technical seminar at the robot manufacturer's facility.

SYSTEM BENEFITS

The robotic coating system is providing measurable advantages in the company's overall coating services. One aspect in particular was significantly advanced—the ability to coat complex shapes. The robot's precise movement and controlled speed allow the spray gun to be positioned to achieve optimal angles in coating complicated parts. To apply a wear-resistant coating on an aircraft engine cowl support, for example, the plasma spray gun must be able to change position to maintain proper orientation while applying a 0.65 in. by 39 in. band of tungsten carbide onto the long, curved part of the cowl. Where only two planes of movement were formerly attainable, the articulating arm robot can address an infinite number of positioning planes. Porosity, oxide content, and coating integrity are optimized.

The application of highly emissive coatings for x-ray targets points up the improvement of coating thickness uniformity. The x-ray target is a disc-shaped object that is rotated at a constant rpm. While it applies a coating on one side of this disc, the robot moves the spray gun across the diameter of the disc at a changing rate of speed inversely proportional to the radius of the disc at the point currently being coated. By maintaining a constant surface speed per minute between the spray gun and part, an even, completely symmetrical film thickness is achieved.

Automatic reproducibility was also upgraded considerably through robotics. Illustrating this improvement is the application of a high-temperature, hard-face coating on a turbine jet engine vane. Used in an extremely hot section of the engine, this component must be coated in those areas where it will come into contact with other parts. The fit between these parts must be precise, requiring that the vane be consistently coated to exacting dimensions of close tolerances.

Variables such as gun to workpiece distance (±0.05 cm) and traverse rate speed are precisely set and repeated. Variability due to operator fatigue is eliminated. Once a coating process is programmed and stored in the robot memory or on tape, the exact procedure can be reproduced time after time, regardless of lot size or length of time between orders.

Hitemco's robotic system has also been responsible for a 25 to 35 percent reduction in order turnaround. This can be attributed to the reduced time required when readying the system for operational changes, making manual adjustments, and performing quality control checks. Previously, time-consuming setups could cause equipment to remain idle until assignments of a similar nature were processed. Now, with minimum time required to shift from one production process to another, maximum use of production equipment can be realized.

THE COATINGS FORECAST

Currently, Hitemco's engineered coatings are being used to ensure the performance of products ranging from liquid rocket motor combustion chambers for geosynchronous satellites, to high-temperature military jet engines, high-speed printer heads, electric switches, firing furnace boats, and x-ray targets. Whether applied through thermal spraying processes (e.g., plasma, oxyacetylene wire/powder, wire arc, and fused) or diffusion (e.g., pack diffusion aluminides and pack diffusion or fused silicides), the objective is to add or alter surface properties for higher reliability and performance. Incorporating robotics into these processes noticeably raises end results on conventionally coated components while concurrently paving the way for new applications. As the technologies in diverse industries evolve, so too will the need for advanced coating technologies that combine the optimum in metallurgical and material properties with robotically controlled application processes.

T.E. Barnard is Vice President and Edwin Garofalo is Senior Production Engineer for Hitemco, Inc.

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The Skywasher

Mobile robots have been rolling into a particular market niche over the past several years. Using wheels and tank tread locomotion techniques, these teleoperated devices perform dangerous jobs in hazardous environments. Tanks including nuclear waste storage, toxic material handling, and civilian and military ordnance disposal are remotely directed by an operator who remains in a safe location.

Continued on the next page.

Photo 1. The Skywasher (preceding page) can move in four directions on the vertical or inclined face of a building.

A new breed of mobile robots from International Robotic Technologies (IRT), Inc. is *walking* into its market niche. IRT has combined an innovative double-body morphology with telescoping legs and actuators to produce a unique building-washing robot called the Skywasher (Photo 1). This robot is able to walk on the vertical and inclined faces of buildings with accurate, preprogrammable motion—both horizontally and vertically.

The Skywasher is approximately 3 ft by 3 ft and weighs 44 lb. (Figure 1). It is equipped with wipers and a washing fluid system that allow it to wash windows, whatever its path down the building face. This system, coupled with the robot's actuators, enables the Skywasher to clean over 50,000 ft^2 of windows in one day, while avoiding holes and passing over obstacles up to 2 in. high and 10 in. wide.

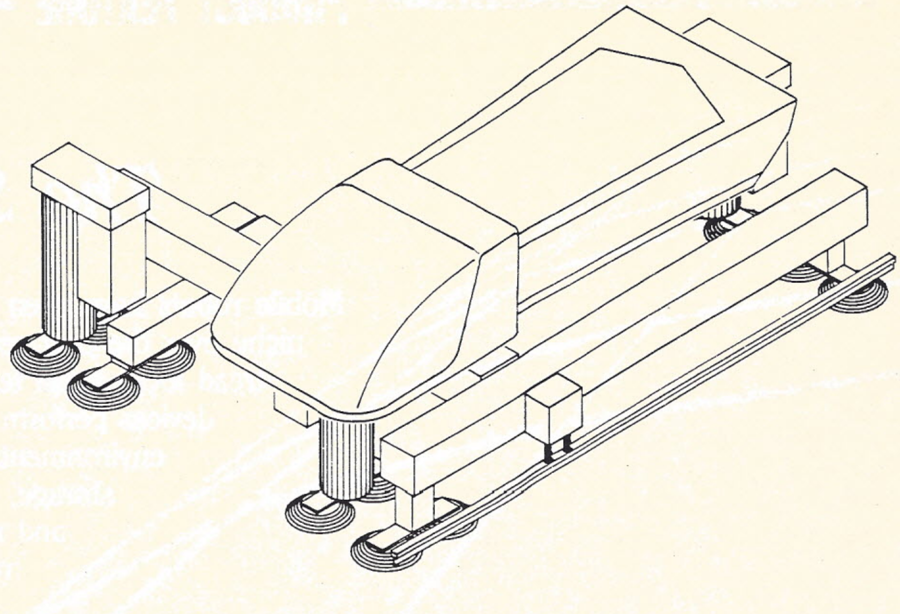


Figure 1. The robot is 3 ft by 3 ft and weighs 44 lb.

INNOVATIVE DESIGN FEATURES

The robot uses its double-body design and suction cup feet to walk on the building in a "sidestep" fashion. Sets of suction cups on the two body structures alternately affix and release, thereby performing the sequence of movements that make up this sidestep (Photo 2).

Another important design feature is the accomplishment of three degrees of freedom using only two actuators. The robot's two main axis actuators, coupled with software routines, provide the additional degree of freedom. The principle is based on a cantilever: One of the two bodies is partially affixed to the building while the other body is extended. The extension creates a cantilever force on the affixed body. By means of software, this force is used constructively to slightly rotate the robot. The technique is used also to correct any deviation from the preprogrammed path (Figures 2 and 3).

WALKING

The Skywasher consists of a main body and a mobile body. Each body has three legs; each leg ends in a pair of vacuum powered suction cups. The legs of the main body are telescoping actuators that allow either the main body or the mobile body or both to be in contact with the building at any given time. The two bodies alternately advance and "catch up" as the robot walks up, down, left, or right.

In the initial action of a step, both bodies are affixed to the surface. Then the telescoping legs are retracted, freeing the main body to advance. After the main body has completed its move, the telescoping legs extend until the main body's feet are affixed to the surface. At this point, the telescoping legs extend the remainder of the stroke, freeing the mobile body to catch up with the main body. When the mobile body has caught up, the main body's legs are retracted and the mobile

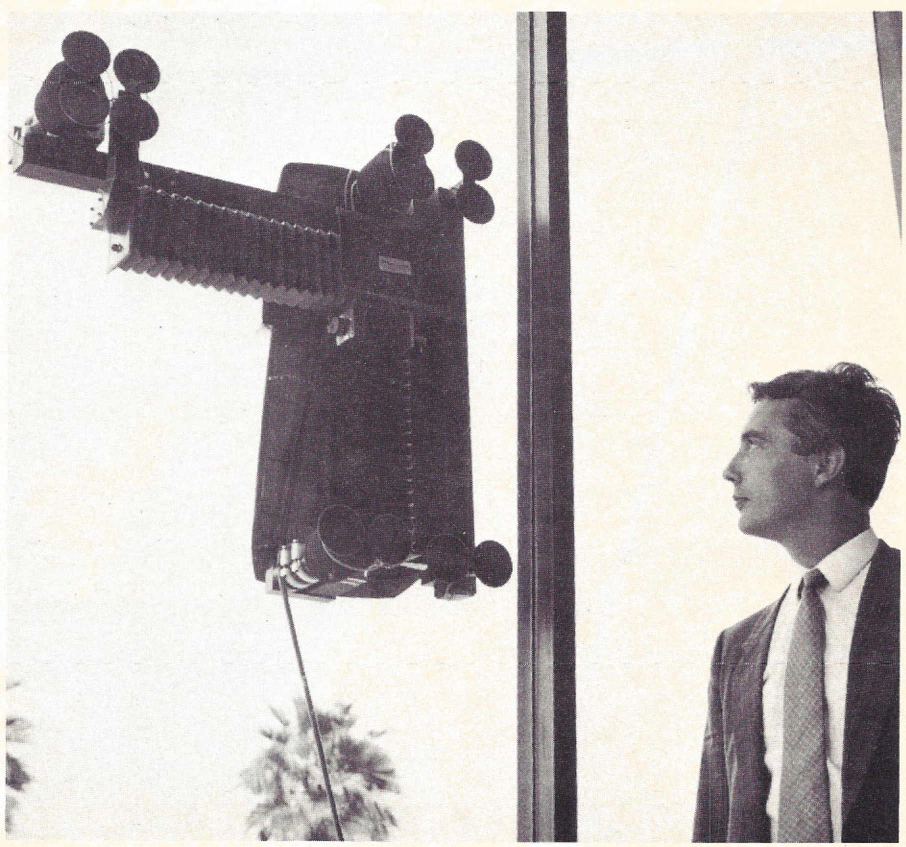


Photo 2. Each of the robot's six legs ends in a pair of vacuum powered suction cups.

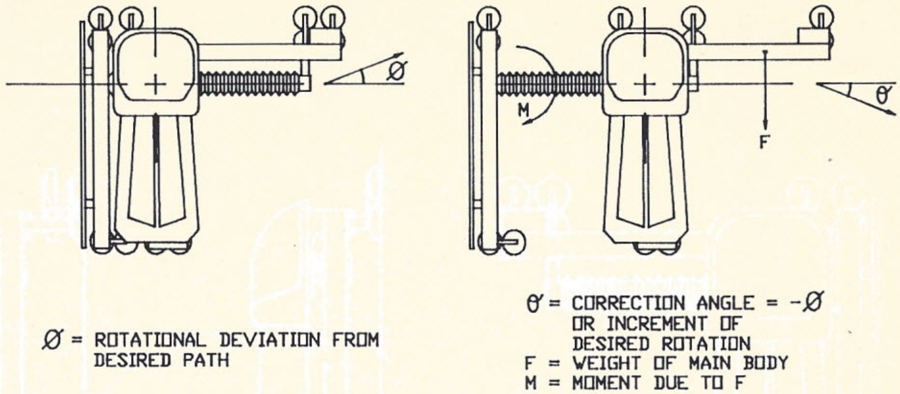
body's feet attach themselves to the surface. Figure 4 illustartes one complete step.

COMPUTER CONTROL

The Skywasher is fully automatic. Once it is programmed for a particular side of a building it can execute the washing sequence each time it is activated. The robot carries an electronics interface on its back, while the main computer remains on the roof (or the ground, in some applications). Data exchange between the robot and the computer takes place at a rate of seven million bits/sec. through fiber optics contained in the robot's umbilical cord.

The ⅝-in. diameter umbilical cord contains the fiber optics, electronic power lines, washing fluid hose, compressed air line, and a safety cable. On the roof, a computer controlled winch feeds the cord to the robot as it travels down the building.

After programming, the operator starts the Skywasher at the top of the building and can leave it unattended to do its work. When its task is finished, the robot returns to its housing, checks its vital functions through an auto-diagnosis program, and waits for its next assignment.



Figures 2 and 3. Rotational error, as shown in Figure 2, is corrected by using a cantilever force to slightly rotate the robot, an operation carried out in software.

SAFETY FEATURES

The suction cup feet on either body can support 300 percent of the Skywasher's weight. These cups are linked separately to the vacuum generators, and they incorporate check valves to maintain full vacuum during a drop in air pressure or a power outage. In addition, sensors in each cup detect insufficient vacuum. If two or more cups are not adequately affixed to the surface, a software routine is executed to position the feet properly.

The umbilical cord winch is synchronized with the robot via computer, automatically following the robot's path to provide a back-up safety line. Even if a power blackout and total suction cup failure were to occur simultaneously, the winch would prevent the robot from falling more than three feet.

OTHER APPLICATIONS

The Skywasher can be equipped with a

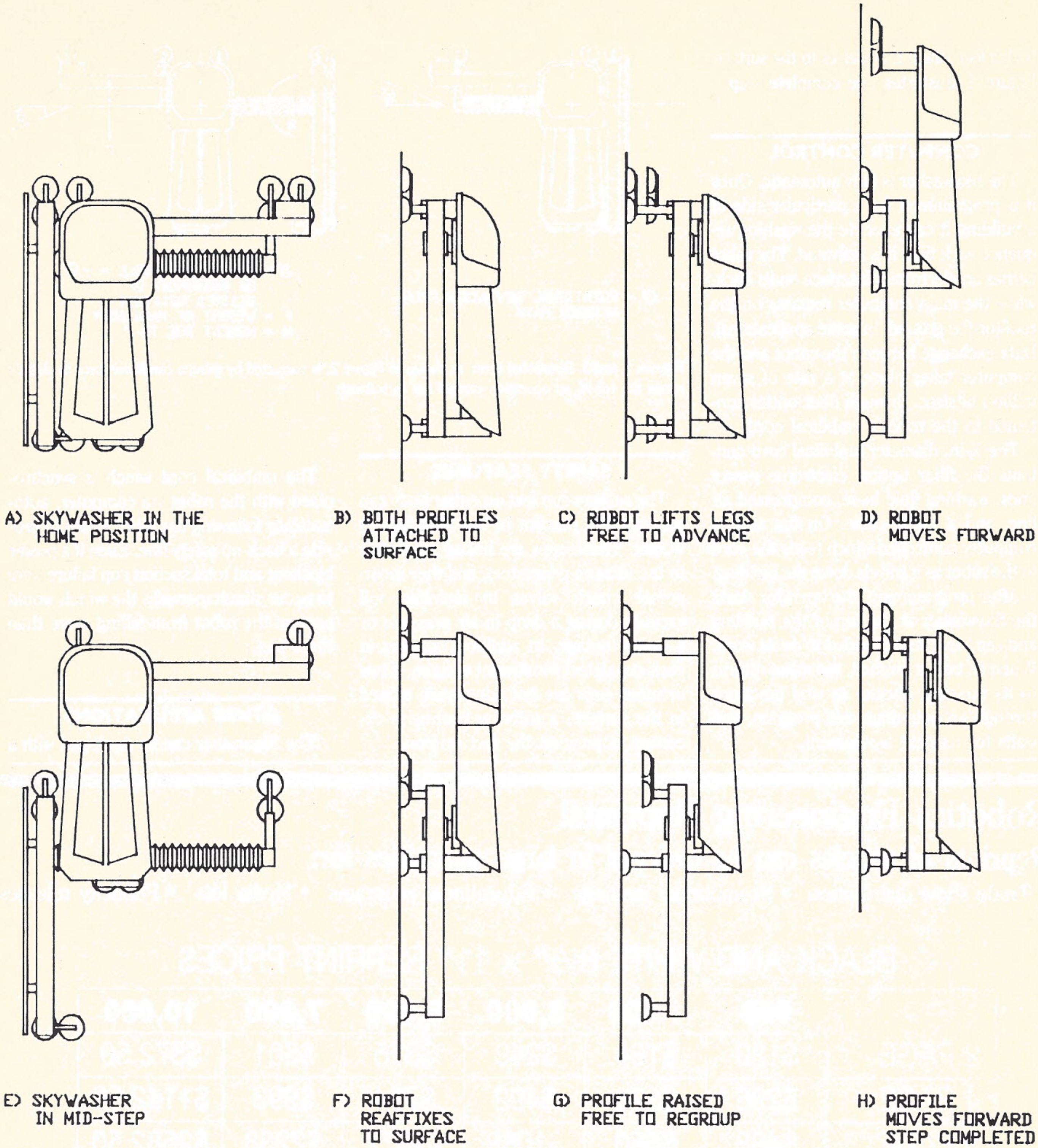


Figure 4. The robot walks by extending one of its two bodies and moving the other body to "catch up" with the first.

video camera that uses a pattern recognition process to inspect building facades. It can also be outfitted with thermal sensors that detect heat loss around window edges or infrared sensors to detect intruders in the building. Variations of the Skywasher are being developed to perform other processes on large vertical surfaces. Cleaning, inspecting, prepping, and painting oil storage tanks, airplanes, and ships are only a few of the jobs ahead for this new breed of sure-footed mobile robot.

Acknowledgements

The Skywasher was invented by robotics engineer Patrice Kroczynski and developed by Brian Wade and electronics engineers Cory Simon and Steve Prager.

International Robotic Technologies
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Marina del Rey, California 90292

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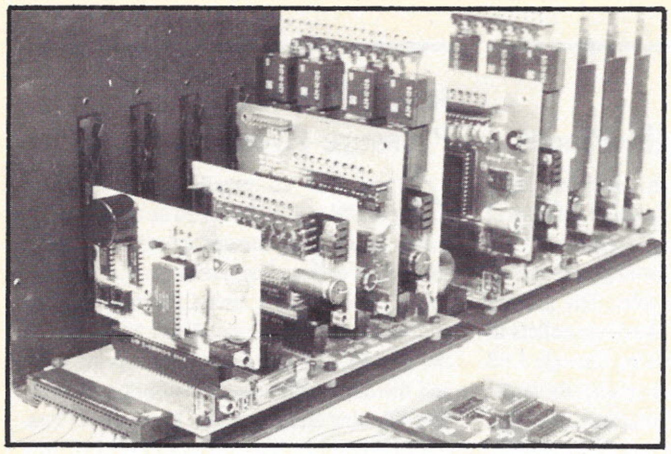
6	16	26
Excellent	Good	Fair

The Amazing A-BUS

NEW



An A-BUS system with two Motherboards
A-BUS adapter (IBM) in foreground

Plug into the future

With the A-BUS you can plug your PC (IBM, Apple, TRS-80) into a future of exciting new applications in the fields of control, monitoring, automation, sensing, robotics, etc.

Alpha's modular A-BUS offers a proven method to build your "custom" system today. Tomorrow, when you are ready to take another step, you will be able to add more functions. This is ideal for first time experimenting and teaching.

A-BUS control can be entirely done in simple BASIC or Pascal, and no knowledge of electronics is required!

An A-BUS system consists of the A-BUS adapter plugged into your computer and a cable to connect the Adapter to 1 or 2 A-BUS cards. The same cable will also fit an A-BUS Motherboard for expansion up to 25 cards in any combination.

The A-BUS is backed by Alpha's continuing support (our 11th year, 50000 customers in over 60 countries).

The complete set of A-BUS User's Manuals is available for $10.

About the A-BUS:

- All the A-BUS cards are very easy to use with any language that can read or write to a Port or Memory. In BASIC, use INP and OUT (or PEEK and POKE with Apples and Tandy Color Computers)
- They are all compatible with each other. You can mix and match up to 25 cards to fit your application. Card addresses are easily set with jumpers.
- A-BUS cards are shipped with power supplies (except PD-123) and detailed manuals (including schematics and programming examples).

Relay Card — RE-140: $129
Includes eight industrial relays, (3 amp contacts, SPST) individually controlled and latched. 8 LED's show status. Easy to use (OUT or POKE in BASIC). Card address is jumper selectable.

Reed Relay Card — RE-156: $99
Same features as above, but uses 8 Reed Relays to switch low level signals (20mA max). Use as a channel selector, solid state relay driver, etc.

Analog Input Card — AD-142: $129
Eight analog inputs. 0 to +5V range can be expanded to 100V by adding a resistor. 8 bit resolution (20mV). Conversion time 120us. Perfect to measure voltage, temperature, light levels, pressure, etc. Very easy to use.

12 Bit A/D Converter — AN-146: $139
This analog to digital converter is accurate to .025%. Input range is −4V to +4V. Resolution: 1 millivolt. The on board amplifier boosts signals up to 50 times to read microvolts. Conversion time is 130ms. Ideal for thermocouple, strain gauge, etc. 1 channel. (Expand to 8 channels using the RE-156 card).

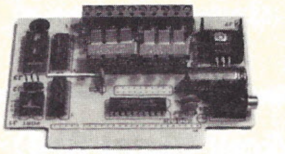
Digital Input Card — IN-141: $59
The eight inputs are optically isolated, so it's safe and easy to connect any "on/off" devices, such as switches, thermostats, alarm loops, etc. to your computer. To read the eight inputs, simply use BASIC INP (or PEEK).

24 Line TTL I/O — DG-148: $65
Connect 24 input or output signals (switches or any TTL device) to your computer. The card can be set for: input, latched output, strobed output, strobed input, and/or bidirectional strobed I/O. Uses the 8255A chip.

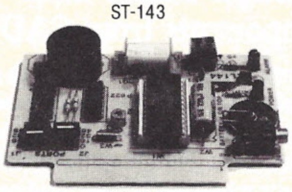
Clock with Alarm — CL-144: $89
Powerful clock/calendar with: battery backup for Time, Date and Alarm setting (time and date); built in alarm relay, led and buzzer; timing to 1/100 second. Easy to use decimal format. Lithium battery included.

Touch Tone® Decoder — PH-145: $79
Each tone is converted into a number which is stored on the board. Simply read the number with INP or POKE. Use for remote control projects, etc.

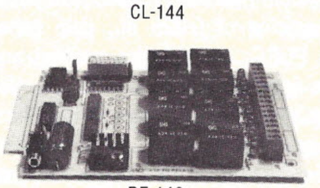
A-BUS Prototyping Card — PR-152: $15
3½ by 4½ in. with power and ground bus. Fits up to 10 I.C.s



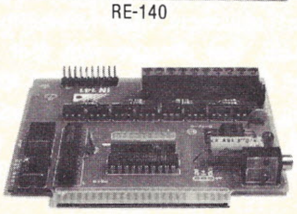
ST-143



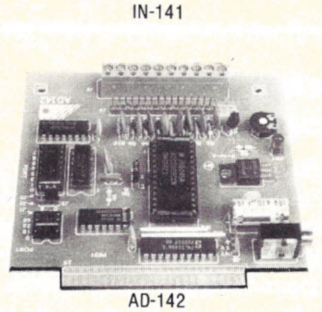
CL-144



RE-140



IN-141



AD-142

Smart Stepper Controller — SC-149: $299
World's finest stepper controller. On board microprocessor controls 4 motors simultaneously. Incredibly, it accepts plain English commands like "Move arm 10.2 inches left". Many complex sequences can be defined as "macros" and stored in the on board memory. For each axis, you can control: coordinate (relative or absolute), ramping, speed, step type (half, full, wave), scale factor, units, holding power, etc. Many inputs: 8 limit & "wait until" switches, panic button, etc. On the fly reporting of position, speed, etc. On board drivers (350mA) for small steppers (MO-103). Send for SC-149 flyer.

Remote Control Keypad Option — RC-121: $49
To control the 4 motors directly, and "teach" sequences of motions.

Power Driver Board Option — PD-123: $89
Boost controller drive to 5 amps per phase. For two motors (eight drivers).

Breakout Board Option — BB-122: $19
For easy connection of 2 motors. 3 ft. cable ends with screw terminal board.

Stepper Motor Driver — ST-143: $79
Stepper motors are the ultimate in motion control. The special package (below) includes everything you need to get familiar with them. Each card drives two stepper motors (12V, bidirectional, 4 phase, 350mA per phase).
Special Package: 2 motors (MO-103) + ST-143: **PA-181: $99**

Stepper Motors — MO-103: $15 or 4 for $39
Pancake type, 2¼" dia, ¼" shaft, 7.5°/step, 4 phase bidirectional, 300 step/sec, 12V, 36 ohm, bipolar, 5 oz-in torque, same as Airpax K82701-P2.

Current Developments
Intelligent Voice Synthesizer, 14 Bit Analog to Digital converter, 4 Channel Digital to Analog converter, Counter Timer, Voice Recognition.

A-BUS Adapters for:

IBM PC, XT, AT and compatibles. Uses one short slot.	AR-133...$69
Tandy 1000, 1000 EX & SX, 1200, 3000. Uses one short slot.	AR-133...$69
Apple II, II+, IIe. Uses any slot.	AR-134...$49
TRS-80 Model 102, 200 Plugs into 40 pin "system bus".	AR-136...$69
Model 100. Uses 40 pin socket. (Socket is duplicated on adapter).	AR-135...$69
TRS-80 Mod 3,4,4D. Fits 50 pin bus. (With hard disk, use Y-cable).	AR-132...$49
TRS-80 Model 4P. Includes extra cable. (50 pin bus is recessed).	AR-137...$62
TRS-80 Model I. Plugs into 40 pin I/O bus on KB or E/I.	AR-131...$39
Color Computers (Tandy). Fits ROM slot, Multipak, or Y-cable.	AR-138...$49

A-BUS Cable (3 ft, 50 cond.) — CA-163: $24
Connects the A-BUS adapter to one A-BUS card or to first Motherboard.
Special cable for two A-BUS cards: CA-162: $34

A-BUS Motherboard — MB-120: $99
Each Motherboard holds five A-BUS cards. A sixth connector allows a second Motherboard to be added to the first (with connecting cable CA-161: $12). Up to five Motherboards can be joined this way to a single A-BUS adapter. Sturdy aluminum frame and card guides included.

Add $3.00 per order for shipping.
Visa, MC, checks, M.O. welcome.
NY residents add sales tax.
C.O.D. add $3.00 extra.
Canada: shipping is $5
Overseas add 10%

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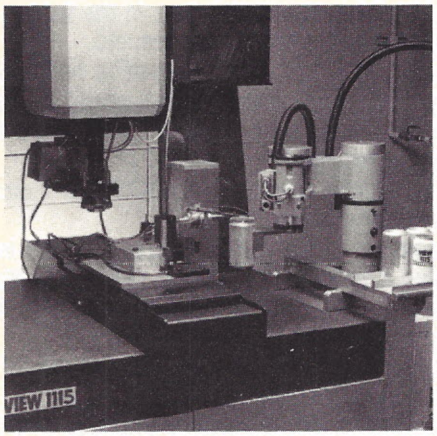
Orders only (Except in NY) **800 221-0916**
New York orders: **(718) 296-5916**
All lines open weekdays 9 to 5 Eastern time

Circle 30

New Products



Workcell Measures Can Bodies

What is described as the first complete workcell for measuring aluminum can bodies examines trim height, dome depth, flange width, plug diameter, and wall thickness, the latter with an accuracy of 50 millionths of an inch. The Seiko TT-3000 transfers cans from the conveyor to the proper inspection stations for in-process and final product, verifying can type automatically before performing the inspection.

Final measurements are processed in a statistical analysis unit and the results displayed on a CRT. Stats are also available in hard copy.

For more information, contact: View Engineering, Inc., 1650 N. Voyager Ave., PO Box 8101, Simi Valley, CA 93063, telephone (805) 522-8439. **Circle 61**

AGV Has 5500-Lb. Payload

A new horizontal/vertical AGV comes equipped with a fork lift unit that includes a telescoping mast for lifting, lowering, or transferring unit loads of up to 5500 lb. The vehicle is preprogrammed to follow an in-floor guide wire. The HV-5 control system is microprocessor based to give a high degree of programmability to the AGV and flexibility to vehicle controls. The AGV can also be easily interfaced with other material handling equipment or systems.

For more information, contact: Control Engineering Co., 8212 Harbor Springs Rd., Harbor Springs, MI 49740, telephone (313) 553-1294. **Circle 62**

End Effector Reaches into Tight Places

The Collet Gripper can reach into tight spots and accurately position cylindrical objects, solving problems frequently encountered with three- or four-fingered end-of-arm tooling used for such jobs. The gripper uses standard off-the-shelf Hardinge collets to offer a size range from 0.016 in. through 1.03 in. in 0.001 in. steps. Custom models for larger sizes and other shapes including triangles, squares, and special tapers are also available. All run on clean shop air of 30 to 125 psi.

For more information, contact: Chuck Haas, Director of Marketing, Robotic Accessories, 4191 U.S. Rte. 40, Tipp City, OH 45321, telephone (513) 667-5705. **Circle 63**

Jaws Distribute Pressure Evenly

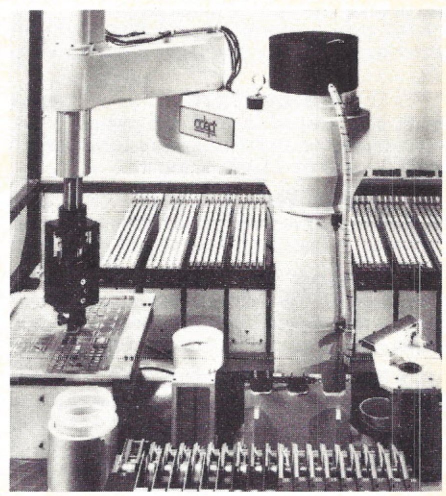
A new line of pneumatically operated parallel jaws is described as exerting firm, evenly distributed pressure across the gripping surface, as opposed to most jaws that close in an arc. The jaws are useful for both internal and external pickup operations and come in two models, one with power-close/spring-open and the other with power-open/spring-close action, allowing continual grip during power loss. Both models are made of stainless steel with brass fittings.

For more information, contact: Charles K. Watters, President, AMi/Assembly Machines, Inc., 2400 Yoder Dr., Erie, PA 16505, telephone (814) 838-8646. **Circle 64**

Workcell Places SMD Components from CAD Data

A new workcell said to be able to precisely place components on board artwork uses a CAD-generated database of placement locations, i.e., there are no taught placement points. The system handles 172-pin quad packs with lead spacing of 0.025 in., chip capacitors, LCCs, PLCCs, electrolytic capacitors, and transistors from 1.5 to 33.7 mm in size. Using an AdeptOne robot with Ruler Vision, the system features on-line manual and full pendant support for cell control, error correction, and selective parts placement. Other features include an automatic tool changer with four vacuum nozzles, four cameras, multiplexing, specialized lighting, board fixturing, and any combination of tray, tube, and tape feeders.

For more information, contact: Jeff Stover,



Gelzer Systems Co., 425 Enterprise Dr., Westerville, OH 43081, telephone (614) 888-2344. **Circle 65**

Storage System Serves Gantry Robot

A line of storage cabinets and systems offers robotic storage and retrieval for the metalworking industry, material handling, plant maintenance and operations, automotive, aviation, electrical, electronic and controls, hospitals, labs, and other industries and services. Ruggedized ABS holders fit into a modular structural frame to accept rotary tools, either straight or tapered shank. A keyway locator on the holder ensures the tool's proper positioning relative to the end effector and insertion into the machine-tool spindle, magazine, or AGV. The gantry robot is programmed to store and retrieve any tool within the system and deliver it to the conveyance for delivery.

For more information, contact: Lista International Corp., 106 Lowland St., PO Box 107, Holliston, MA 01746-2031, telephone (617) 429-1350. **Circle 66**